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RESEARCH AND DEVELOPMENT OF A CAVITATING WATER JET CLEANING SYS--ETC(U)
JUN 78 S C HOWARD, F C GRAHAM, A A HOCHREIN N00014-77-C-0367
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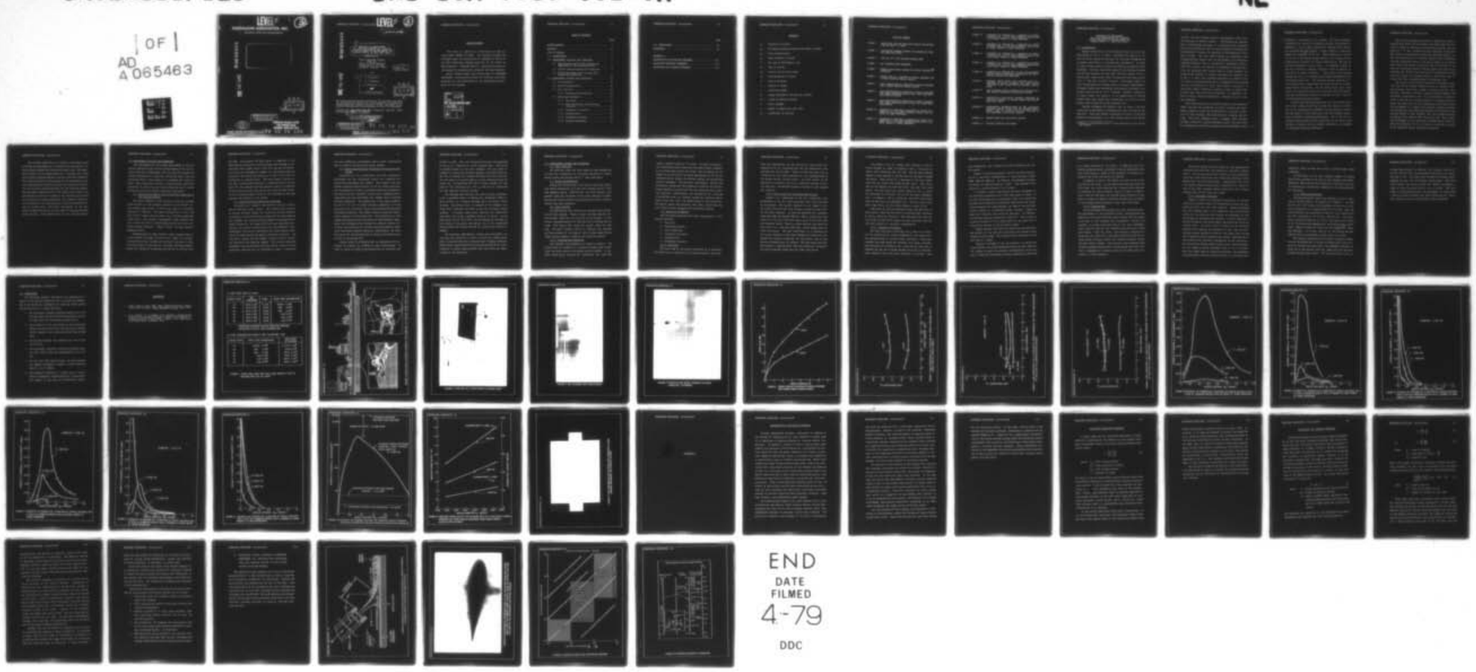

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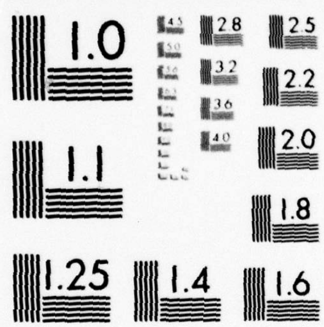

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RESEARCH AND DEVELOPMENT OF A CAVITATING WATER JET CLEANING SYSTEM FOR REMOVING MARINE GROWTH AND FOULING FROM U. S. NAVY SHIP HULLS.

Submitted to:

Ship Technology Program
Code 221
Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

(12) 61p.

by

(10)

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Prepared for the Office of Naval Research, Code 221, under Contract No. (15) N00014-77-C-0367

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ACKNOWLEDGMENTS

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Messrs. Dwight Koogle and William Boyd of DAEDALEAN ASSOCIATES, Incorporated provided the technical assistance necessary for the fulfillment of the engineering requirements of this program.

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NOTATION

I_e - intensity of erosion

P_i - the impact pressure arising from bubble collapse

P_o - free stream pressure

P_v - vapor pressure of liquid

R - the size of the bubble or jet

Δt - time of erosion

V_o - velocity of the free stream

Δy - drilling depth of erosion

A - area of cleaning

ρ - density of liquid

σ - cavitation number

E - energy absorbed by the material removed

ΔV - volume of material removed

S - scale strength

n - number of impacts per unit time

C_v - coefficient of velocity

LIST OF FIGURES

RESEARCH AND DEVELOPMENT OF A CAVITATING WATER JET CLEANING SYSTEM FOR REMOVING MARINE GROWTH AND FOULING FROM U. S. NAVY SHIP HULLS

1.0 INTRODUCTION

Energy conservation in the operating fleet is one of the major goals of the U. S. Navy. Increased hull drag as a result of marine growth and fouling has long been recognized as a primary contributor to increased fuel consumption. In order to reduce marine growth, various antifouling coatings have been developed. The most successful among the antifouling coatings are the Navy formulas 121 and 1020A. The Navy formula 121 is a conventional copper-based vinyl coating which has been used by the U. S. Navy for the past 20 years. The formula 1020A is a vinyl based organo-tin coating which is currently experimental. The copper-based vinyl coating has experienced a reasonably successful service life of 20 to 36 months. However, experience in tropic waters has shown it to be ineffective for periods greater than nine months and occasionally as little as three months, particularly for slime formation (1)*.

Various estimates (2) indicate that at least a 15% fuel saving can be achieved by minimizing the skin friction of the ship hull. This fuel saving corresponds to about 8.9 million barrels of fuel annually or, at the current price of $21.00/bbl

* Numbers in parentheses refer to the references at the end of this report.

ABSTRACT

of fuel, the fuel savings would be approximately $187.5 million dollars as shown in Figure 1. Paralleling the development of antifouling coatings, it is imperative that alternate means are developed so that the marine growth and fouling can periodically be cleaned. One approach is the underwater cleaning of hulls. The cost effectiveness for underwater hull cleaning greatly depends upon the development of an efficient cleaning technique that is suitable for underwater applications. At present, the majority of underwater cleaning operations are performed with various types of rotary brushes. Although brush cleaning is readily available for immediate use by the U. S. Navy, more advanced techniques are needed so that the removal of marine growth may be accomplished with minimum time and interruption to other ship mission activities. A relatively simple technique is needed in order to remove light fouling from ship hulls more frequently, as compared to removal of heavy fouling infrequently, through the use of complex equipment.

With these objectives in mind the Office of Naval Research (ONR), Code 221, has conducted an initial research and development program to prove the feasibility of utilizing cavitation for hull cleaning and ocean platform cleaning applications. With this technique, water is pumped under pressure through a nozzle of a properly designed system. The high speed jet emerging from the nozzle produces cavitation bubbles which CONT

collapse on the surface to be cleaned. The basic principle involved in the cavitation cleaning technique is discussed in Appendix A. As the high pressure jet emerges from a nozzle of a properly designed system, a large number of cavitation bubbles are produced in the jet. These bubbles are carried by the jet to the marine growth wherein they collapse with a predetermined intensity of erosion required for the type of fouling encountered on ship hulls. A conceptual scheme of how the cavitation cleaning technique could be applied to ship hulls is shown in Figure 2. Large areas can be cleaned through the use of a rotating brush system supplemented with cavitating water jets. The rotating brushes would be of a soft polypropylene composition that would remove the accumulated slimes and grasses. The cavitating water jets would remove the calcareous growth from the hull and would rejuvenate the antifouling surface by removing the first layer of the antifouling coating material.

A diver operated cavitating water jet "gun" would be put into use to remove the fouling on areas that were not accessible to the rotating brush assembly such as propeller surfaces and sea chests in ship applications and for weldment inspection in offshore platform applications. Due to the low reaction forces produced by the cavitating jet, the diver would be able to maneuver the jet readily and would not be exposed to fatiguing operating conditions.

This initial program constituted a feasibility study to ascertain the ability of utilizing a cavitating water jet system as a means of removing the accumulated fouling from the hulls of U. S. Navy vessels and ocean platform structures. This initial investigation yielded the following results: 1) the cavitating water jet technique removed all of the fouling that had accumulated during a 36 month period in the Chesapeake Bay on test panels coated with type 121 coating; 2) not only was the fouling removed from the panels, but also of significance was the fact that the layers of antifouling coating were left intact; 3) cleaning rates of 1125 ft^2/hr were attained with this technique using 9.9 horsepower (hp).

The results of the initial feasibility evaluation indicate that various design parameters such as cleaning rates, area covered, nozzle size, number of nozzles required, fouling type, thickness, velocity, pressure pumping capacity and horsepower requirements need to be investigated further in order to identify the system parameters and design specifications. The definition of these parameters would characterize the development of a simple and versatile cleaning technique for periodically refurbishing ship hulls and would save a significant amount of fuel annually. The cost savings have been estimated on the order of $187 million per year. The successful development of the cavitation cleaning system would enhance the capability of the U. S. Navy in attaining the goals of the shipboard energy conservation program.

The ultimate objective is to develop a prototype system utilizing the phenomenon of cavitation jet cleaning for removing marine growth and fouling from ship hulls. The underwater system will be demonstrated as a prototype unit after the necessary engineering data collection has been completed. The overall objective of the program will be achieved by properly evaluating the specific feasibility aspects and gathering the necessary engineering data for the prototype design. The successful demonstration of this phase would require the optimization of the area cleaned by the cavitation jet system as an additional design requirement. The complete design matrix required for the prototype unit would be developed during the second phase. The actual development of the unit would be completed during the final phase of the program which would include a field demonstration of the cleaning system.

2.0 EXPERIMENTAL FACILITY AND TECHNIQUES

The requirements for the design and assembly of the laboratory apparatus along with the establishment of the test facility have been accomplished. The test facility consists of several subsystems for producing cavitating water jets and evaluating their effectiveness as a technique for scale removal. These subsystems include: 1) high pressure water flow subsystem; 2) monitoring and control subsystem; and 3) nozzle performance and scale removal evaluation subsystem.

2.1 High Pressure Water Flow and Delivery Subsystem to the Cleaning Nozzles

The major component of the delivery system for the high pressure water to the cleaning nozzles is a horizontal triplex plunger pump capable of delivering 5 gpm at a developed pressure of 7,500 psi. The pump is powered by a 25 hp, 460 volt, 60 Hz, 3 phase, electric motor via a multiple power band V-belt drive. The constant displacement pump produces the volume flow rate from a reciprocating action with close tolerance plunger diameters. Figure 3 shows the high pressure pumping facility.

Complementing the high pressure triplex plunger pump is a low pressure (50 psig) filtered water supply to the pump; a starter and circuit breaker protection for the motor, a rupture disc relief protection for the pump; and high pressure valves and tubing for by-passing and control of the flow from

the pump. Low pressure (50 psig) water is supplied to the high pressure horizontal triplex plunger pump through a conventional water supply source. This flow can also be diverted to fill an environmental chamber for controlled condition testing of the cavitating nozzles or to fill a test tank for evaluation of cleaning rates. The water supply pressure to the pump is monitored to maintain a required positive suction head. The flow through the high pressure nozzle is regulated by the nozzle pressure control and the nozzle by-pass valve. A nozzle pressure gauge located at the discharge of the pump monitors the pressure at the nozzle.

2.2 Control and Instrumentation Subsystem

The pump has a standard shunt-switch electric control and an auxiliary power control. The control panel consists of various pressure gauges for nozzle and suction pressure in addition to specific pressure gauges for the environmental test chamber. The chamber pressure gauges are designated low range (0-160 psi), mid range (0-600 psi) and high range (0-1, 500 psi) for accurate monitoring of the environmental tests. Independent controls are associated with each pressure indicator for gauge protection against excessive pressures. The flow meter control and the chamber pressure control actuate the flow meter and pressure gauges. The critical operating parameters can be monitored from the central control and the necessary functions can be performed in order to determine

the loss coefficient measurements and to gather engineering data on specific orifice plate nozzle designs.

2.3 Nozzle Performance and Cleaning Rate Evaluation Subsystem

Evaluation of loss coefficients and other measures of performance for the cavitating nozzles are conducted in a controlled environment test chamber. The design of the test chamber required proper location of the jet nozzle and standard test material in order to establish cavitation parameters. The nozzle and test material location were designed and incorporated into the environment test chamber with a variable distance capability. The chamber has a test sample capability of 6" x 6" x 2", an offset distance capability of 9" and view ports for cavitation erosion and intensity determination from bubble formation. The chamber permits visual and quantitative analysis of cavitating jets. The flexibility of this chamber makes possible the evaluation of many different types, sizes, and configurations of nozzles in terms of velocity, efficiency and intensity for varying operating pressure conditions and nozzle standoff distances. Additionally, the chamber allows for the determination of erosion resistance of materials to cavitating jets.

Another area of performance that is evaluated is the intensity of erosion, I_e, produced by each nozzle design. In order to carry out these I_e determinations, an intensity test

fixture is used. This test fixture facilitates the gathering of the I_e as a function of nozzle distance data. The nozzle is rigidly mounted in the test assembly. The test panel is clamped in a small vise directly opposite the nozzle position. The vise is mounted on a movable platform that will allow for the test panel to be positioned at various distances from the nozzle tip. By measuring the time to erode through the test panel by the cavitating jet, the I_e value can be calculated for that specific distance setting.

The cleaning rate data for the various nozzle configurations is gathered using a cleaning rate mechanism, Figure 4, which consists of a movable carriage and a stationary nozzle assembly. The fouled plate is mounted on the movable carriage which translates the plate across the stationary nozzle assembly. A variable speed motor controls the translation rate which may attain a maximum value of 15 in/sec. As the plate moves across the nozzle, the cavitating jet impinges on the surface of the plate and removes all of the accumulated marine growth and fouling leaving the antifouling coating undamaged.

The necessary experimental studies and preliminary design data were generated to define the specific design parameters associated with the cavitation hull cleaning technique. Additionally, the feasibility of utilizing the cavitation clean-technique to remove marine growth from ship hulls was demonstrated in the laboratory.

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Test Objective

The objective under the first phase of this program was to prove the feasibility of utilizing cavitation to remove marine growth and fouling from U. S. Navy ship hulls.

3.2 Nozzle Configuration

During the initial phase, two orifice sizes were evaluated which constituted an 0.042 inch diameter and an 0.047 inch diameter nozzle. Additionally, two swirl inducers, #45 and #46, were also evaluated. These swirl inducers in combination with the two nozzle sizes provided six nozzle configurations that were evaluated.

3.3 Test Facility

An experimental test facility was designed and calibrated for this program. Figure 3 shows the high pressure triplex plunger pump that was utilized in the program. It develops a maximum pressure of 7500 psi with a maximum flow of 5 gpm. This figure also shows the control panel for this pump. The panel contains valves to regulate the pressure and flow produced by the pump as well as high range and low range pressure gauges to monitor the pressure produced.

3.3.1 Cleaning Rate Mechanism

The cleaning rate mechanism is shown in Figure 4. The fouled plate is mounted on a movable carriage which translates the plate across a stationary nozzle assembly. A variable speed motor controls the translation rate which may

attain a maximum speed of 15 in/sec. As shown in Figure 5, the fouled plate moves across the stationary nozzle assembly. As the plate moves across the nozzle, the cavitating jet impinges on the surface of the plate and removes all of the accumulated marine growth and fouling leaving the antifouling coating undamaged. The necessary experimental studies and preliminary design data were generated to define the specific design parameters associated with the cavitation hull cleaning technique. Additionally, the feasibility of utilizing a cavitating water jet cleaning system for removing marine growth from ship hulls was demonstrated in the laboratory. The marine growth and barnacles have been removed from the test plates without damaging the antifouling coating.

3.4 Operating Parameters

The operating parameters that were investigated in this program included:

a. Flow rate
b. Operating pressure
c. Loss coefficient
d. Intensity of erosion
e. Cleaning rate
f. Horsepower utilized

3.4.1 Flow Rate

The first step in the nozzle evaluation is to determine the flow rate as a function of the nozzle pressure. From this

flow rate information, the jet velocity for each nozzle configuration can be calculated and the loss coefficient comparisons can then be made. Figure 6 shows the flow rate as a function of the nozzle pressure for two configurations of the single orifice conical nozzle. For each nozzle, as the pressure is increased, there is a resultant increase in nozzle flow rate. The maximum pressure utilized in this program was 7,000 psi.

3.4.2 Loss Coefficient and Operating Pressure

Figure 7 is a comparison of the loss coefficient (C_v) performance of the two nozzle diameters that were evaluated in the program. The C_v data depicted in the figure is for the 0.042 inch and 0.047 inch diameter conical nozzles without the swirl inducers. C_v data was gathered for a pressure range from 1000 psi through 7000 psi. The C_v values were nominally 0.74 for the 0.047 inch nozzle and 0.55 for the 0.042 inch diameter nozzle. These C_v values indicate that the 0.047 inch nozzle is a much more efficient nozzle design than the 0.042 inch nozzle. The loss coefficient is a comparison of the actual velocity of the water through the nozzle with the theoretical velocity predicted for the nozzle size at some discrete pressure level of interest. The data shows the 0.047 inch nozzle is approximately 20% more efficient throughout the entire pressure range than the 0.042 inch nozzle.

The effects on C_v for adding swirl inducers to the two nozzle designs is shown in Figures 8 and 9. Two swirl inducers were evaluated, #45 and #46. The #45 swirl inducer imparts a more vigorous or violent swirl to the water through the nozzle. This results in a decrease in the loss coefficient for any nozzle size using the #45 swirl. This can be seen in the figures for both the 0.042 inch and 0.047 inch nozzle. For the 0.042 inch nozzle, Figure 8, the C_v values are decreased to 0.50 from 0.55 in the non-swirl configuration. In Figure 9, the C_v values for the 0.047 inch nozzle with the #45 swirl are nominally 0.57. This is a much lower value than the C_v for the nozzle without a swirl (0.74).

Additional C_v data was gathered using the #46 swirl in both nozzles. When the #46 swirl is utilized slight increases in the C_v values are realized. This indicates that the nozzles using the #46 swirl inducer are more efficient than the same size nozzle in a non-swirl configuration.

3.4.3 Intensity of Erosion

The next step after collecting the C_v data is to evaluate the intensities of erosion produced by the various nozzle configurations at several nozzle distances. These measurements are made using the intensity test stand. An aluminum test plate is affixed in the stand and the time that is required for the jet to break through the plate at some specific pressure level and nozzle distance is recorded. From

this information, the intensity vs nozzle distance curve can be created.

Figure 10 contains intensity data for the 0.042 inch nozzle in a non-swirl configuration at three pressure levels 3000, 5000 and 7000 psi. At 7000 psi, the maximum intensity of erosion is 2400 watts/meter^2 (w/m^2). This maximum value occurs at a nozzle distance of 0.5 inches.

In Figures 11 and 12 the effects of swirl inducement on the intensity produced by the 0.042 inch nozzle is shown. It has been discovered that by inducing a swirl in a nozzle the optimum nozzle distance is decreased. With swirls the intensities produced are approximately the same as the non-swirl nozzle, however at a decreased nozzle distance. Figure 11 shows the intensity data with the #46 swirl. At 7000 psi, the maximum intensity produced is 2900 w/m^2. This occurs at a nozzle distance of 0.125 inches which is less than the 0.5 inch nozzle distance of the non-swirl nozzle.

Figure 12 shows the 0.042 inch nozzle with the #45 swirl. The severity of the #45 swirl decreases the optimum nozzle distance still further. The optimum nozzle distances are now less than 0.1 inches.

Figures 13 through 15 are the intensity vs nozzle distance data for the three configurations of the 0.047 inch nozzle. Figure 13 shows the non-swirl configuration of the nozzle. At 7000 psi the maximum intensity generated is 6200 w/m^2

at a nozzle distance of 1.0 inches. At 5000 psi with this nozzle configuration the intensity of erosion produced by the 0.047 inch nozzle is equal to the intensity of erosion produced by the 0.042 inch nozzle at 7000 psi.

In Figures 14 and 15 the effects of swirl on the 0.047 inch nozzle are shown. As was discussed previously with the 0.042 data, the swirls decrease the optimum nozzle distance yet maintain the same intensity level as a nozzle without a swirl. With the #46 swirl the optimum nozzle distance is less than 0.1 inches at 7000 psi and with the #45 swirl in Figure 14 the optimum nozzle distance is less than 0.05 inches.

3.4.4 Cleaning Rate

After gathering the intensity and loss coefficient data, the performance of the individual nozzle configurations was analyzed so the most effective nozzle design could be chosen to be used in the cleaning rate evaluations. During this analysis, it became clear that none of the swirl configurations could be used for the cleaning rates and still yield good results. With the swirls, the intensity envelope produced does not allow for a very great deviation from the optimum nozzle distance before the maximum intensity values decrease rather rapidly. These nozzles were dismissed from further consideration because a nozzle design with that critical a dependence on distance could not be effectively utilized in a field operation.

The nozzle design that was chosen for the cleaning rate evaluation was the 0.047 inch nozzle in a non-swirl configuration. For all pressure levels tested in the C_v determinations the 0.047 inch nozzle was a much more efficient nozzle design than the 0.042 inch nozzle. Additionally, the 0.047 inch nozzle produced much greater intensities of erosion at each of the three pressure levels tested than did a similar configuration of the 0.042 inch nozzle.

3.4.5 Threshold Intensity

Figure 16 shows the threshold intensities of erosion values for the Navy Formula 121 antifouling coating, the barnacles and also the steel hull material. Before proceeding into the cleaning tests, it was imperative that the threshold values for the barnacles and coating be determined so that the parameters governing jet intensity could be adjusted to yield an intensity that would remove the fouling yet leave the coating intact. As can be seen in Figure 16, the threshold intensity for removing the barnacles is less than the antifouling coating threshold intensity. This means that fouling can be removed without removing the coating. Superimposed on this figure is the intensity envelope for a 0.047 inch nozzle. With this nozzle design, marine growth can be removed throughout the range of nozzle distances from 0.1 to 3.5 inches. With this large range of operating distances, the dependency of maintaining a specific nozzle distance is alleviated and,

therefore, would be much more easily utilized under field conditions.

At this point in the test program, samples of fouled plates were obtained to be used in the cleaning rate determinations. These plates were originally coated with the type 121 antifouling coating and submerged in the Chesapeake Bay for 36 months.

3.4.6 Measured Horsepower

The measured power output and cleaning rate as a function of nozzle diameter is presented in Figure 17. At 3000 psi for the 0.047 nozzle the horsepower utilized is 4.5 hp. This corresponds to a cleaning rate of 15 in^2/sec. When the nozzle pressure was increased to 5000 psi, the cleaning rate was also increased to 45 in^2/sec (1125 ft^2/hr). The horsepower utilized at 5000 psi is 9.9 hp. The plates were cleaned of all fouling without damaging the antifouling layers underneath. Figure 18 shows the results of the CONCAVER(TM) cleaning technique. It is seen that all of the fouling has been removed and the antifouling coating layers are intact.

The research conducted in the present program has demonstrated the feasibility of using cavitating water jets to remove the fouling from ship hulls. The CONCAVER technique removed all of the fouling from the sample and left the antifouling coating layer intact. For the 0.047 inch nozzle at

an operating pressure of 5000 psi, the cleaning rate was 45 in^2/sec (1125 ft^2/hr). The horsepower utilized at this pressure was 9.9 hp. The plates were cleaned of fouling without damaging the type 121 antifouling coating layer. With this nozzle design, the marine growth was removed throughout a range of nozzle distances from 0.1 to 3.5 inches. With this range of operating distances, the dependency on maintaining a specific nozzle distance has been alleviated and, therefore, would be easily utilized under field conditions.

4.0 CONCLUSIONS

The following specific conclusions are summarized as a result of the initial feasibility for utilizing the phenomenon of cavitation as a technique for removing marine growth and fouling from U. S. Navy ship hulls.

1. The cavitation cleaning technique removed all of the fouling from a heavily fouled test specimen and left the Navy type 121 antifouling coating intact.

2. The intensity of the cavitating jet was controlled during the testing such that the fouling was removed without damage to the substrate antifouling coating layer.

3. The maximum cleaning rate produced was 1125 ft^2/hr (45 in^2/sec).

4. The horsepower utilized to obtain the maximum cleaning rate (1125 ft^2/hr) was approximately 10 hp (9.9 hp).

5. For the 0.047 inch nozzle design, the marine growth was removed throughout a range of nozzle distances from 0.1 to 3.5 inches.

6. The threshold intensity of erosion was 2.5 watts/$meter^2$ for barnacle removal and was 6.2 watts/$meter^2$ for removal of the type 121 antifouling coating.

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2. H. S. Preiser, C. P. Cologer, H. E. Achilles, "Energy (Fuel) Conservation Through Underwater Removal and Control of Fouling on Hulls of Navy Ships," Report 4543, NSRDC Materials Department, December, 1975.

I) FUEL COST FOR U.S. NAVY

FISCAL YEAR	BBL. CONSUMED	$/BBL.	TOTAL FUEL EXPENDITURE
73	45.9×10^6	$ 3.20	$146.9 $\times 10^6$
*74	31.4×10^6	15.75	495 $\times 10^6$
75	57.6×10^6	16.50	950 $\times 10^6$
76	58.9×10^6	17.99	1.06×10^9
77	59.6×10^6	18.90	1.13×10^9
78	59.4×10^6	21.00	1.25×10^9

*PRESIDENT'S ENERGY SAVING DIRECTIVE ORDERED REDUCTION IN FLEET FUEL CONSUMPTION

II) FUEL CONSUMPTION PENALTY DUE TO FOULING : 15%

FISCAL YEAR	TOTAL FUEL EXPENDITURE	FUEL COST OF FOULING
73	$146.9 $\times 10^6$	$ 22.0 $\times 10^6$
74	495 $\times 10^6$	74.25 $\times 10^6$
75	950 $\times 10^6$	142.5 $\times 10^6$
76	1.06×10^9	159.0 $\times 10^6$
77	1.13×10^9	169.5 $\times 10^6$
78	1.25×10^9	187.5 $\times 10^6$

FIGURE 1 TOTAL FUEL COST AND FUEL COST PENALTY DUE TO FOULING FOR THE U.S. NAVY

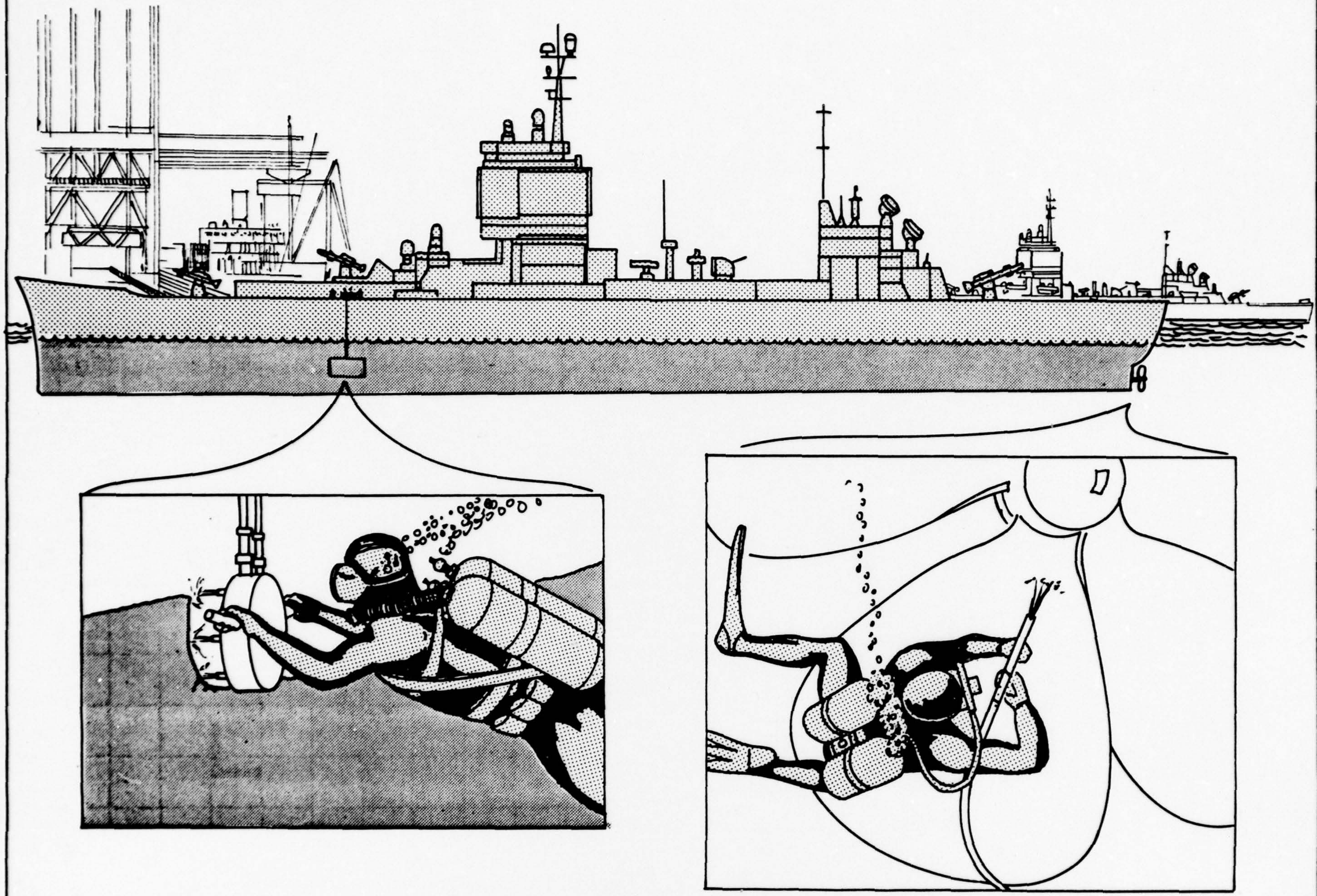

FIGURE 2 CAVITATION CLEANING CONCEPT FOR REMOVAL OF FOULING FROM SHIP HULLS

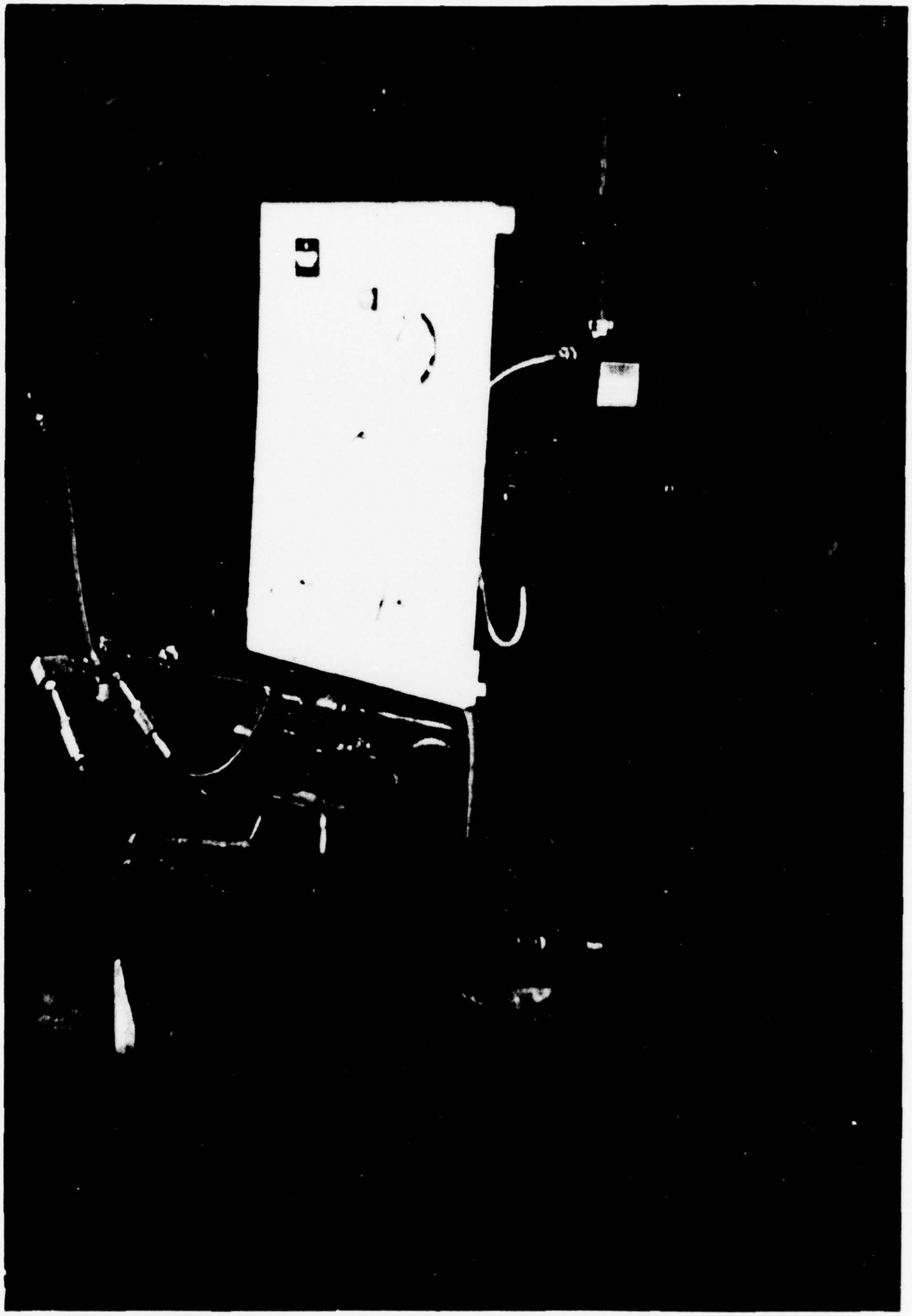

FIGURE 3 7500 PSI AT 5 GPM TRIPLEX PLUNGER PUMP

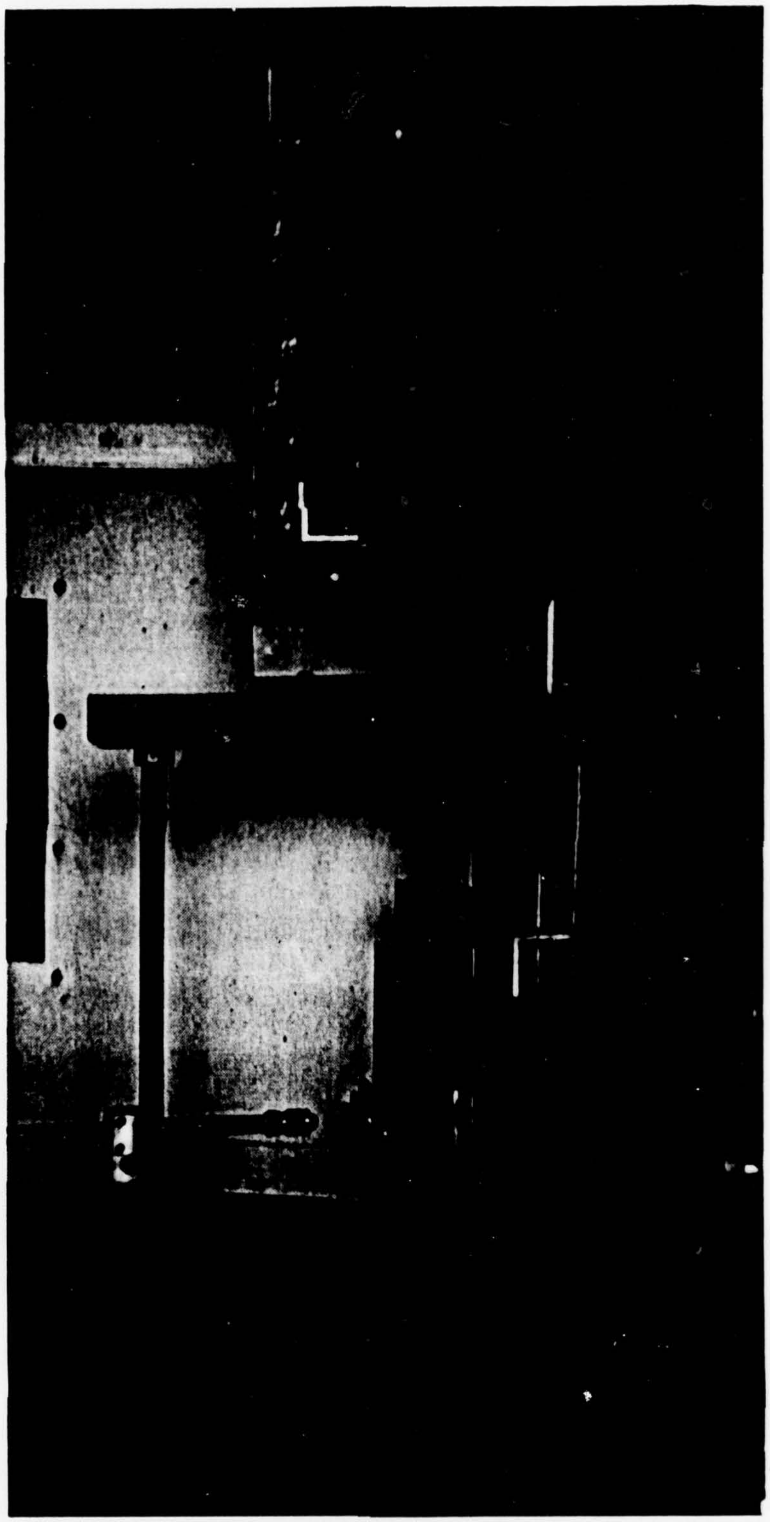

FIGURE 4 DAI CLEANING RATE MECHANISM

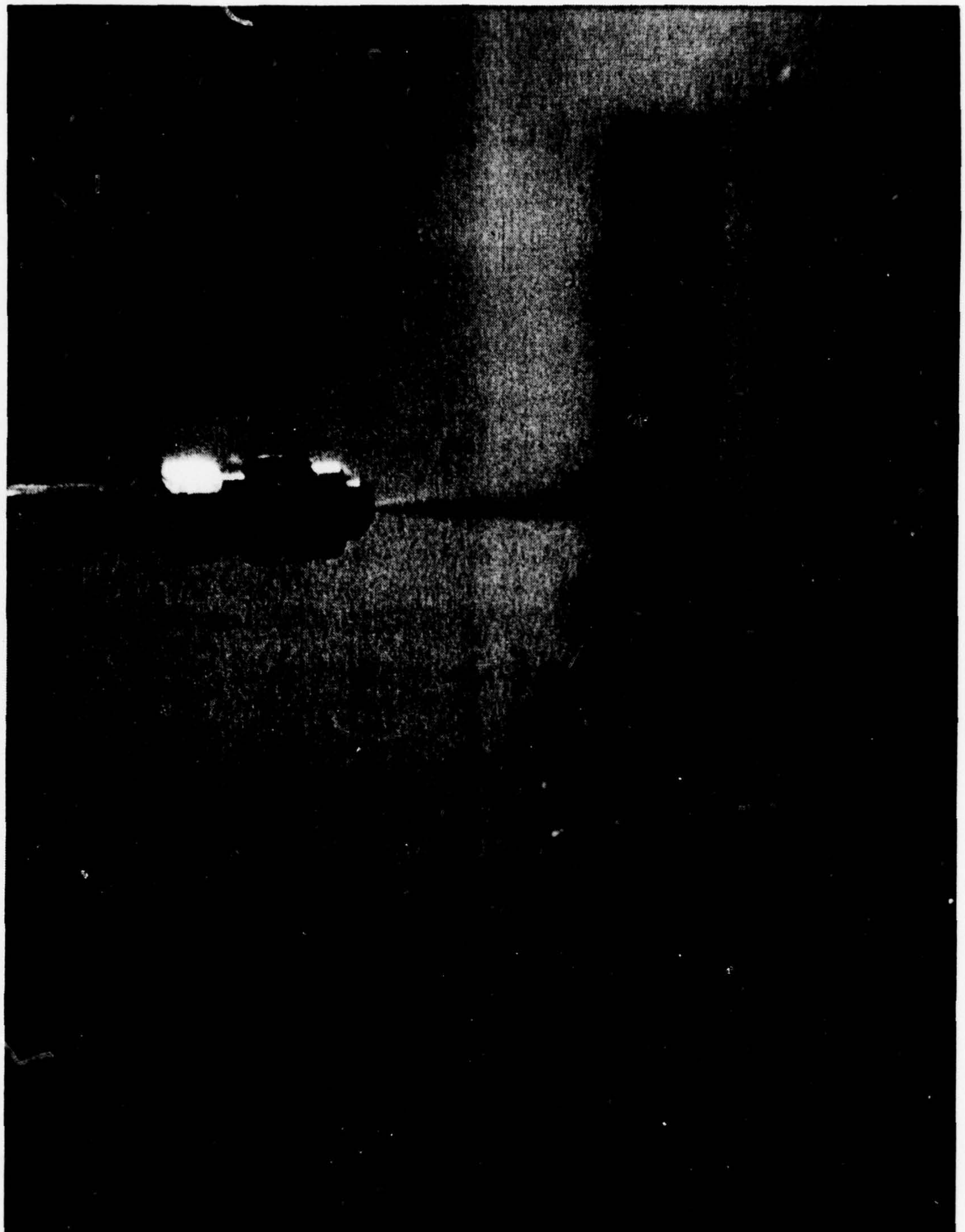

FIGURE 5 FOULED PLATE BEING CLEANED UTILIZING CONCAVER TECHNIQUE

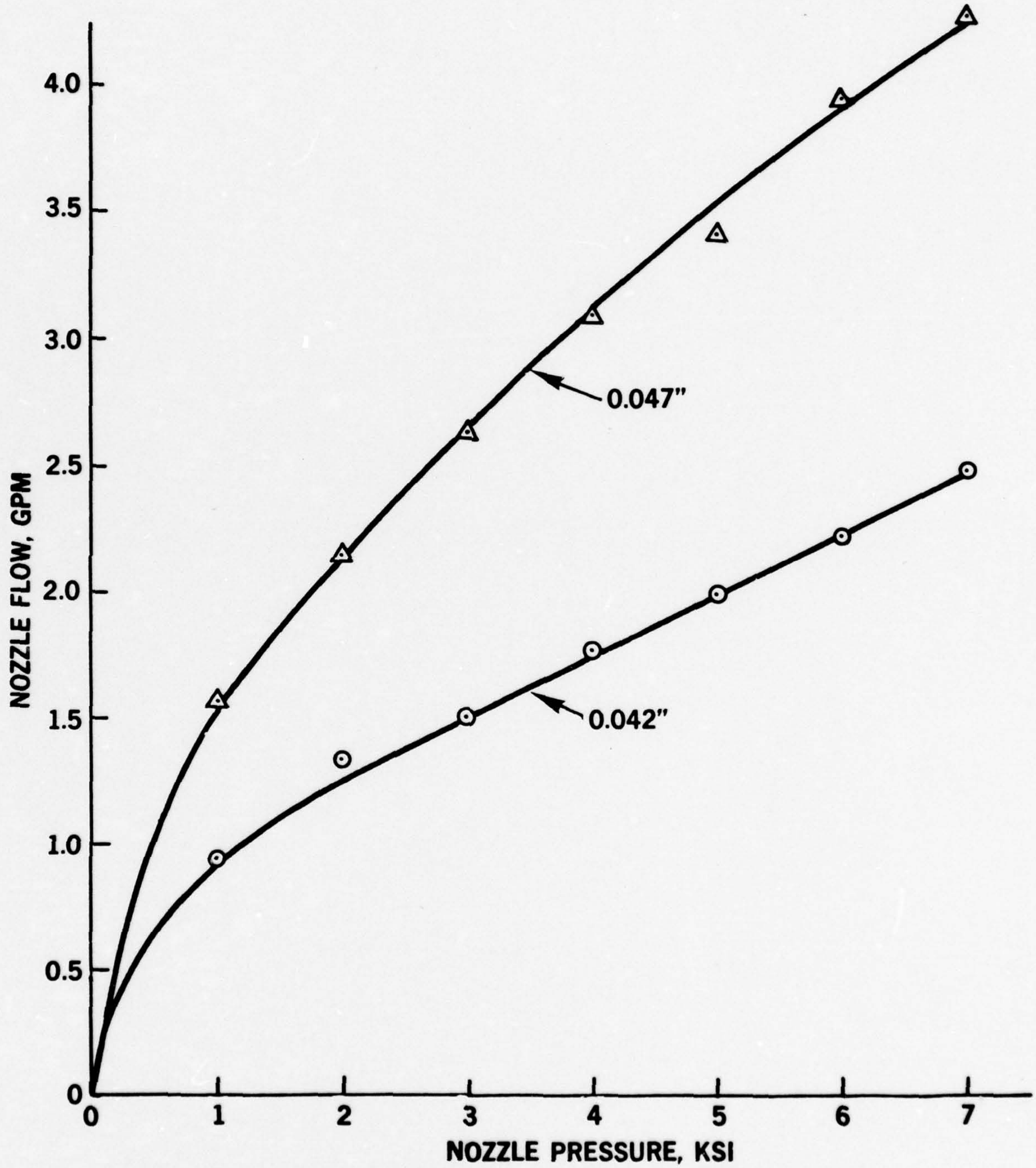

FIGURE 6 NOZZLE FLOW AS A FUNCTION OF NOZZLE PRESSURE FOR A SINGLE ORIFICE CONICAL NOZZLE

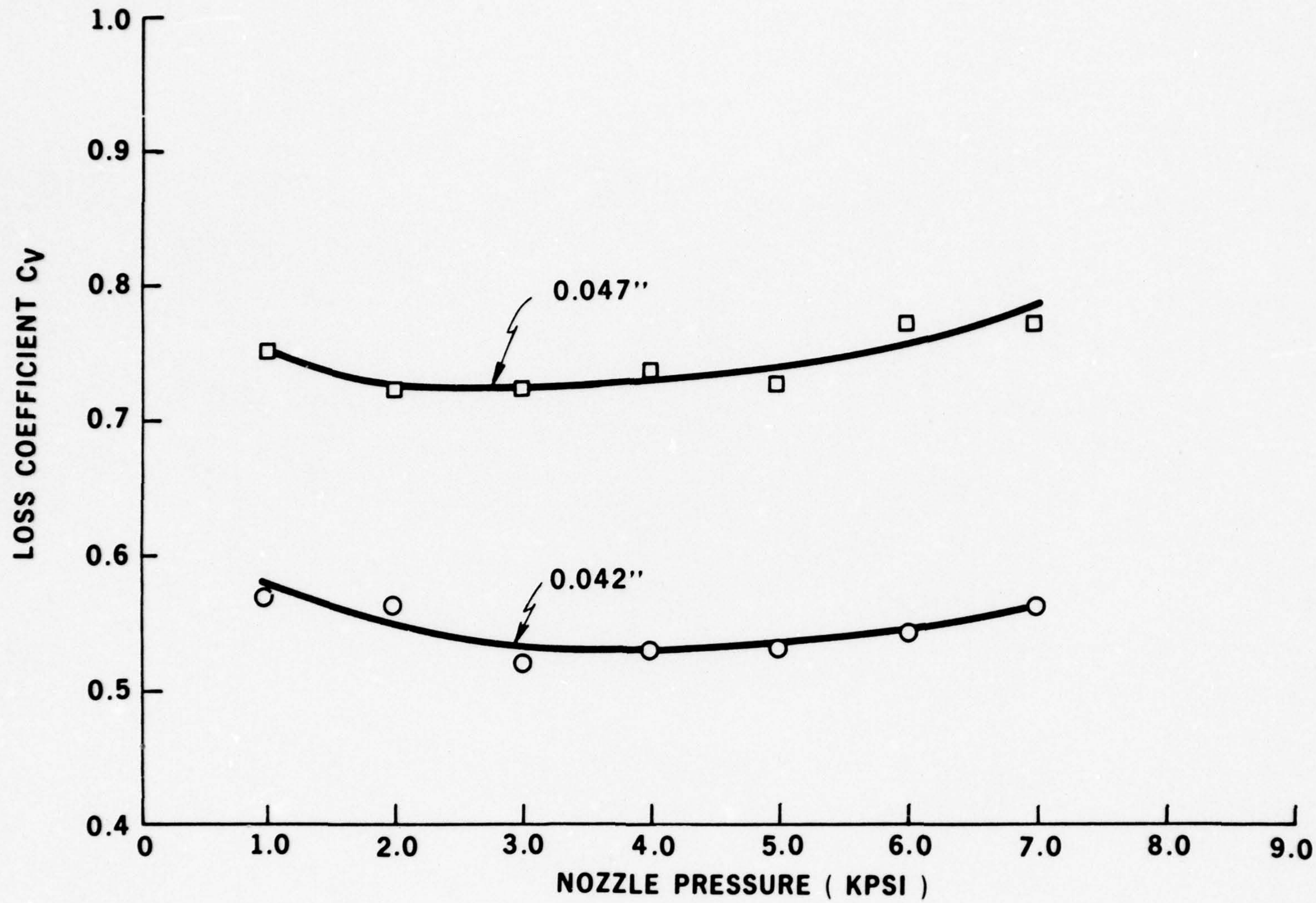

FIGURE 7 LOSS COEFFICIENT AS A FUNCTION OF NOZZLE PRESSURE FOR A SINGLE ORIFICE CONICAL NOZZLE

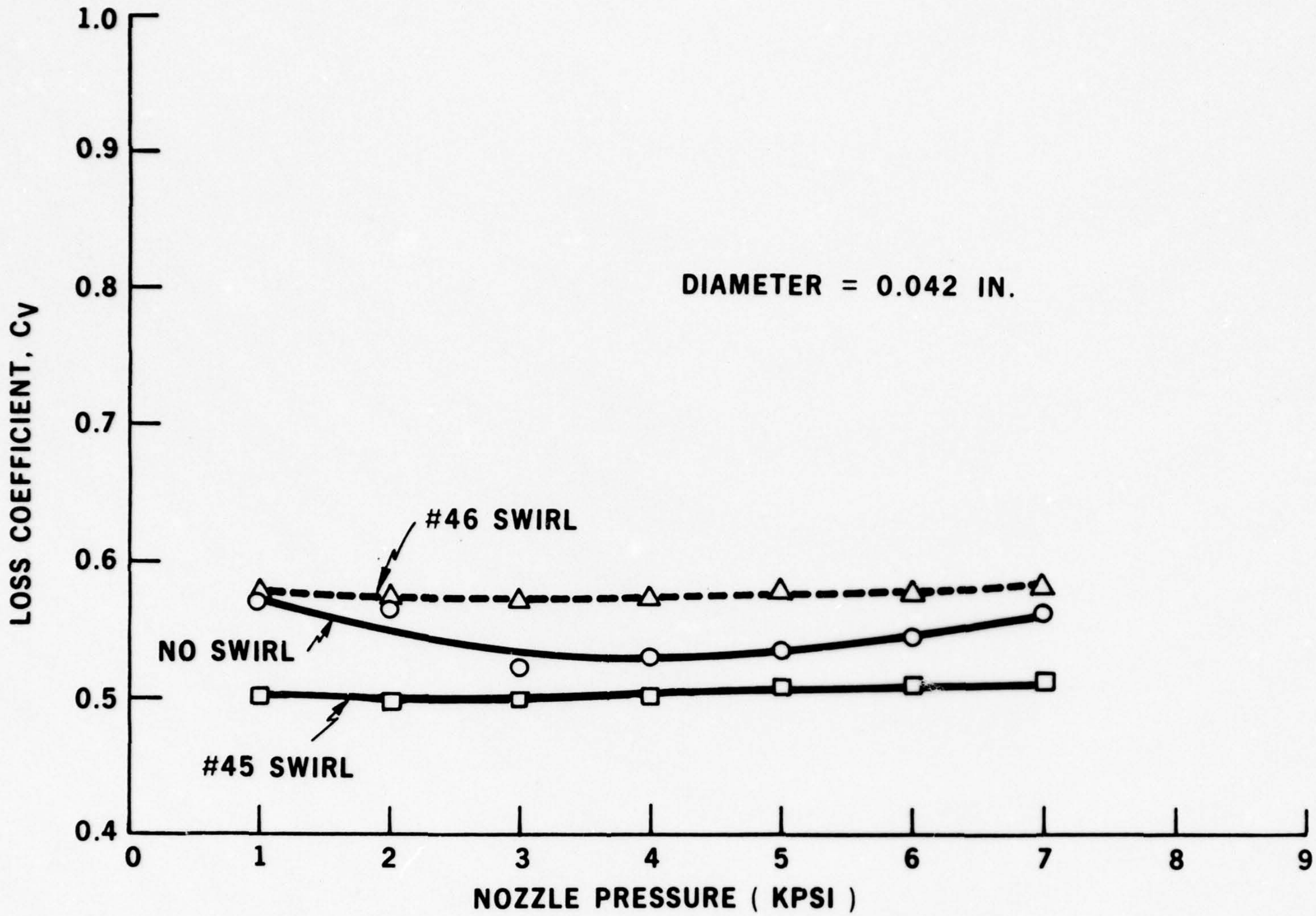

FIGURE 8 LOSS COEFFFICIENT AS A FUNCTION OF NOZZLE PRESSURE FOR THREE CONFIGURATIONS OF THE 0.042 IN. DIAMETER ORIFICE NOZZLE

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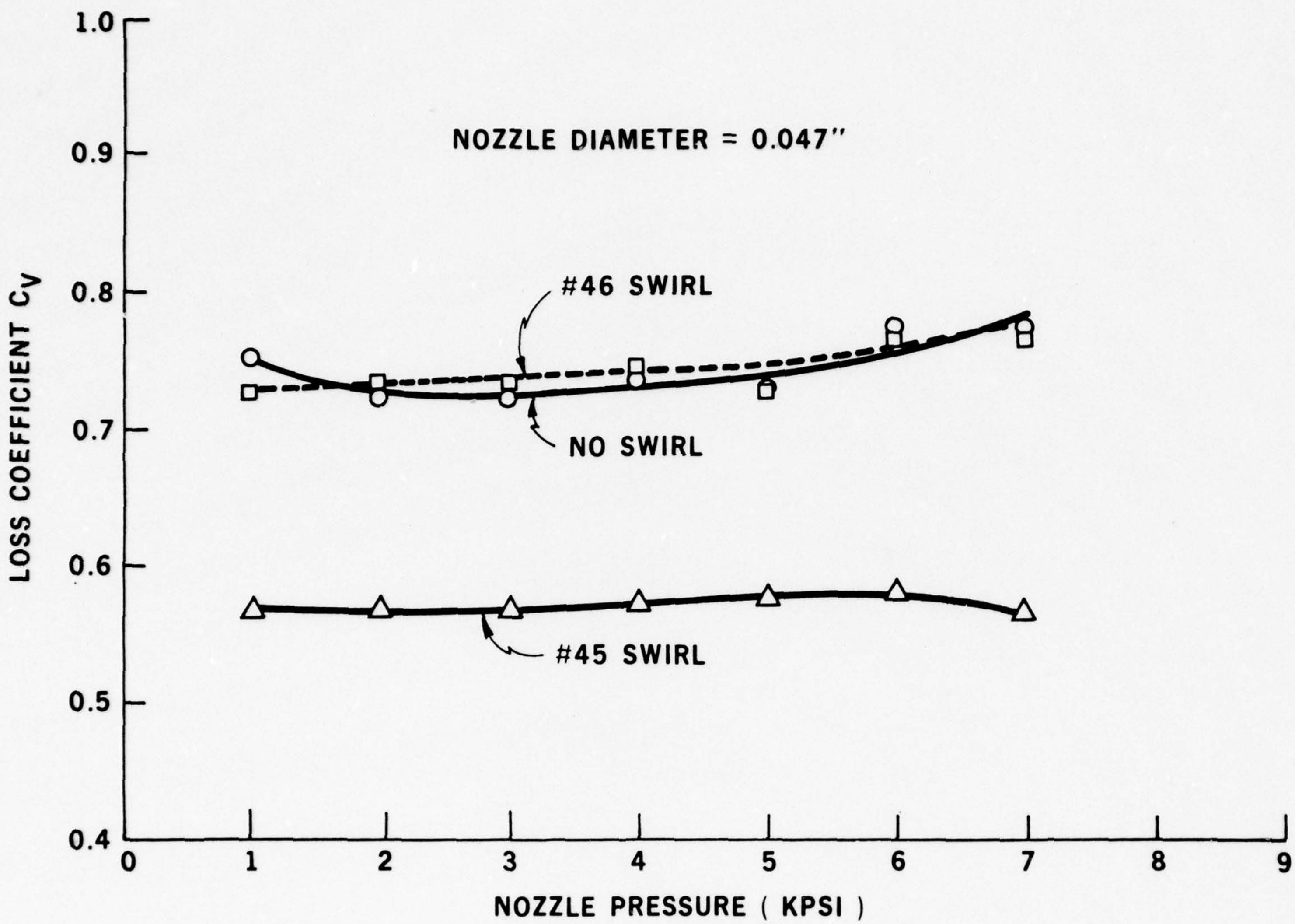

FIGURE 9 LOSS COEFFICIENT AS A FUNCTION OF NOZZLE PRESSURE FOR THREE CONFIGURATIONS OF THE 0.047 IN. DIAMETER NOZZLE

DAEDALEAN ASSOCIATES, Inc.

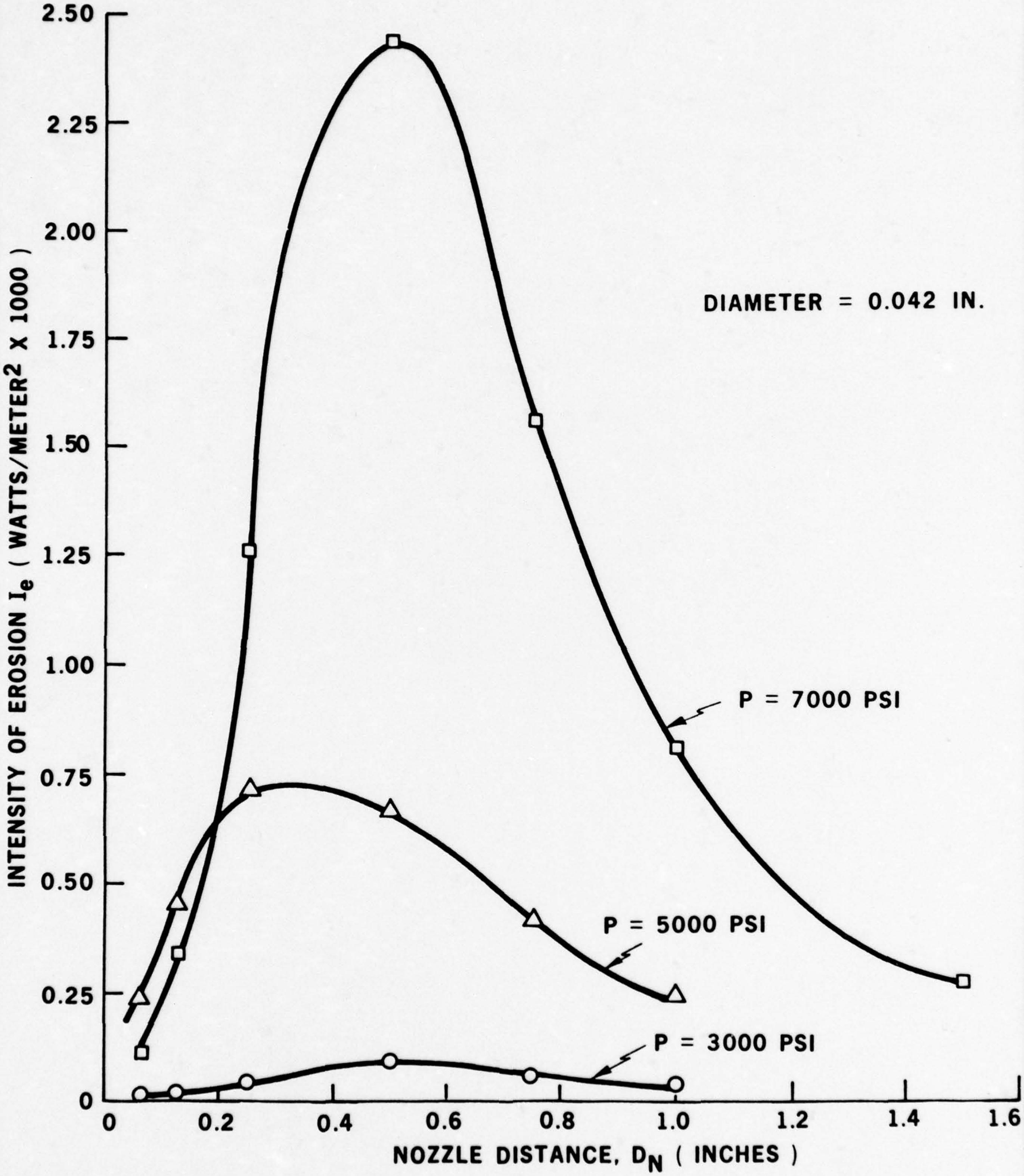

FIGURE 10 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE DISTANCE FOR A 0.042 IN. DIAMETER NOZZLE WITH NO SWIRL AT THREE PRESSURES

DAEDALEAN ASSOCIATES, Inc.

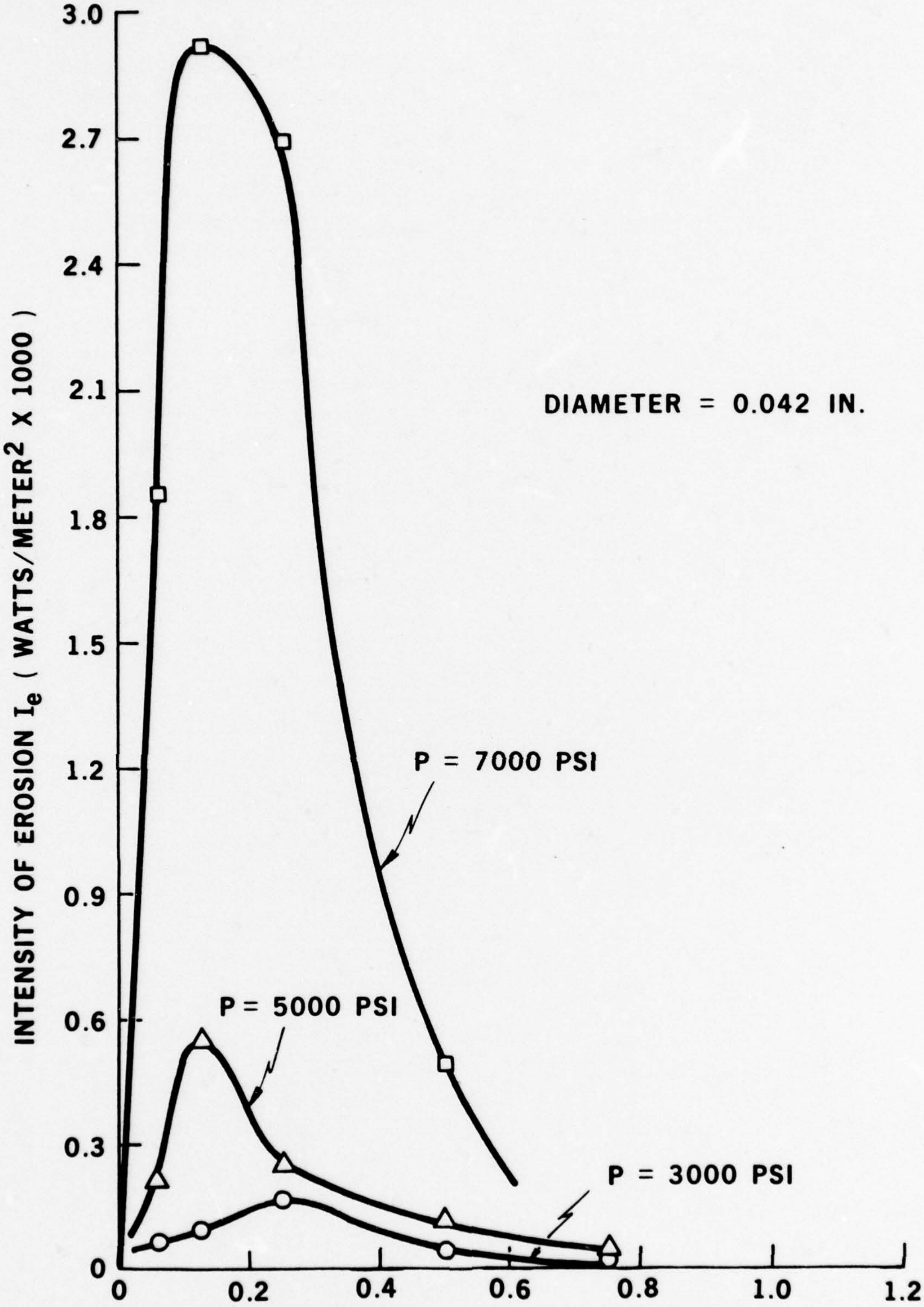

FIGURE 11 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE DISTANCE FOR A 0.042 IN DIAMETER NOZZLE WITH A NUMBER 46 SWIRL INSERT AT THREE PRESSURES

DAEDALEAN ASSOCIATES, Inc.

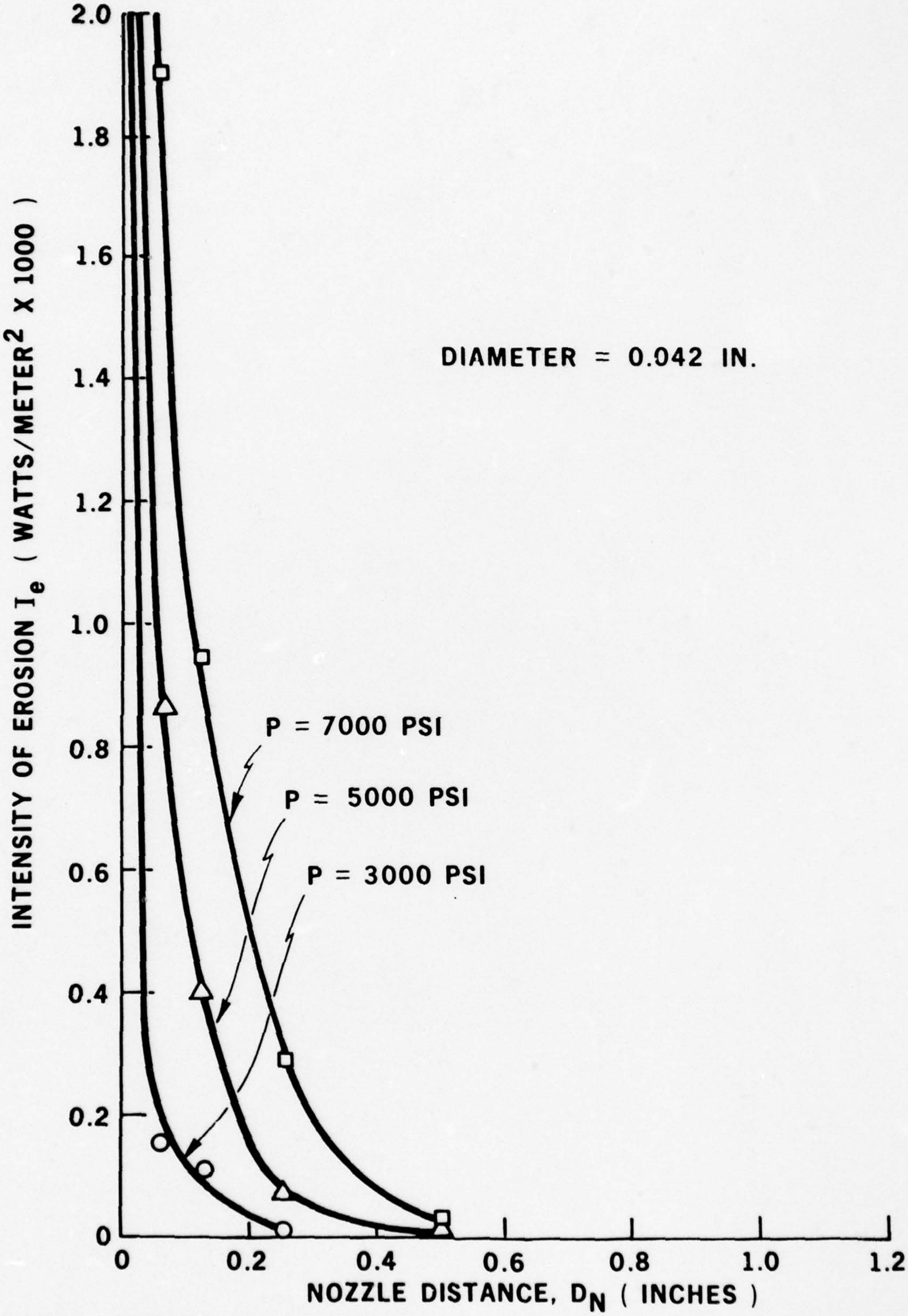

FIGURE 12 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE DISTANCE FOR A 0.042 IN. DIAMETER NOZZLE WITH A NUMBER 45 SWIRL INSERT AT THREE PRESSURES

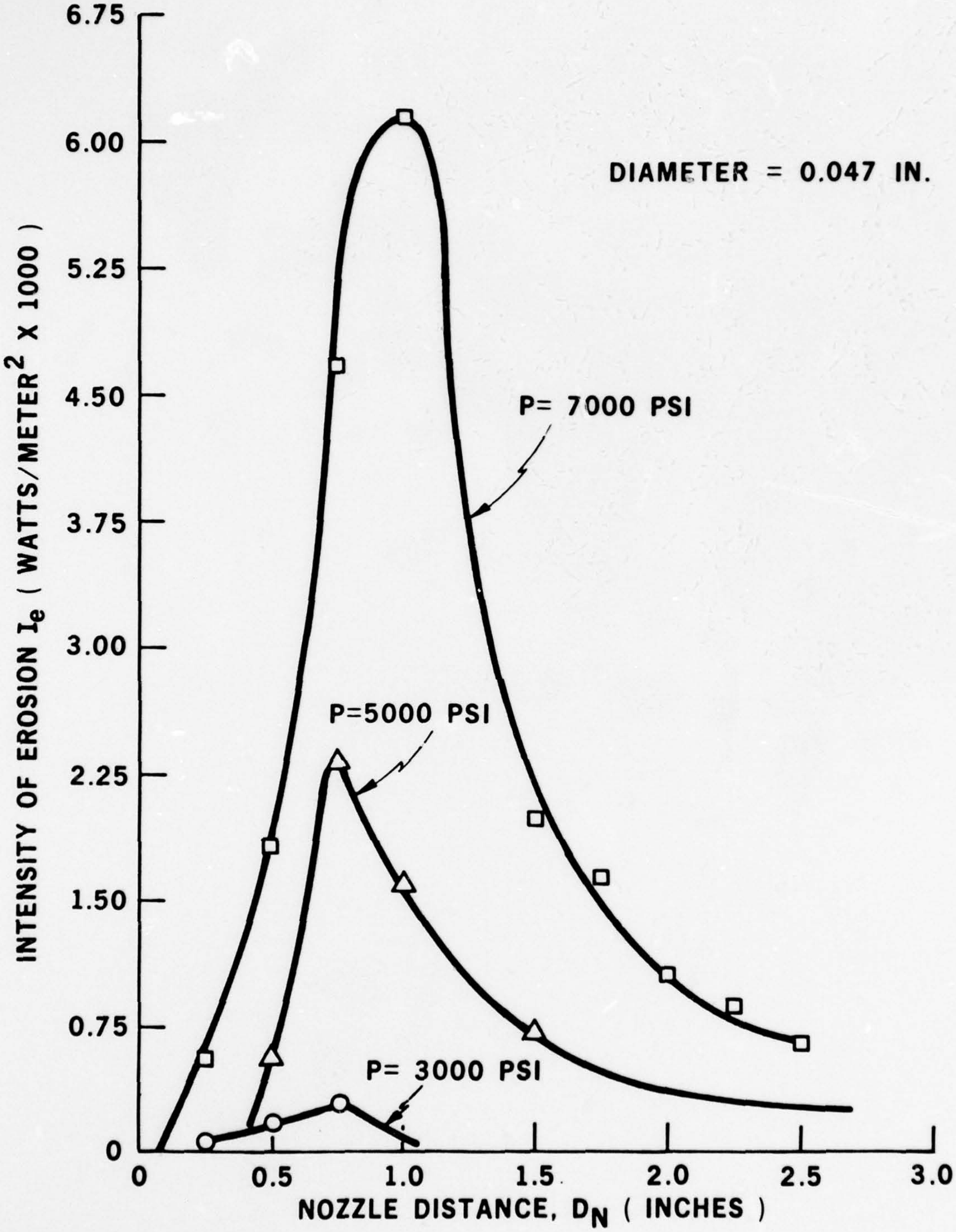

FIGURE 13 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE DISTANCE FOR A 0.047 IN. DIAMETER NOZZLE WITH NO SWIRL INSERT AT THREE PRESSURES

DAEDALEAN ASSOCIATES, Inc.

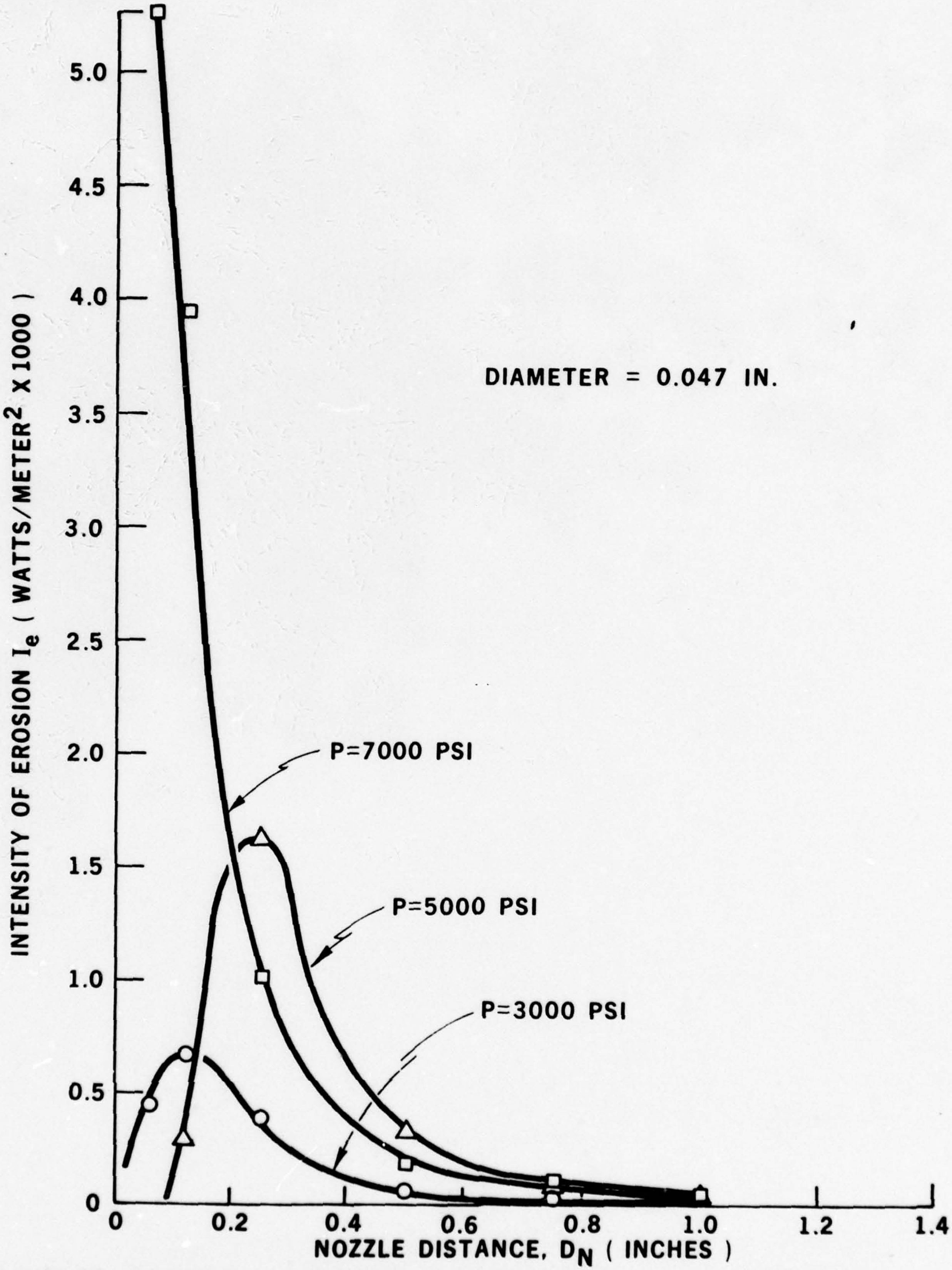

FIGURE 14 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE DISTANCE FOR A 0.047 IN. DIAMETER NOZZLE WITH A NUMBER 46 SWIRL INSERT AT THREE PRESSURES

DAEDALEAN ASSOCIATES, Inc.

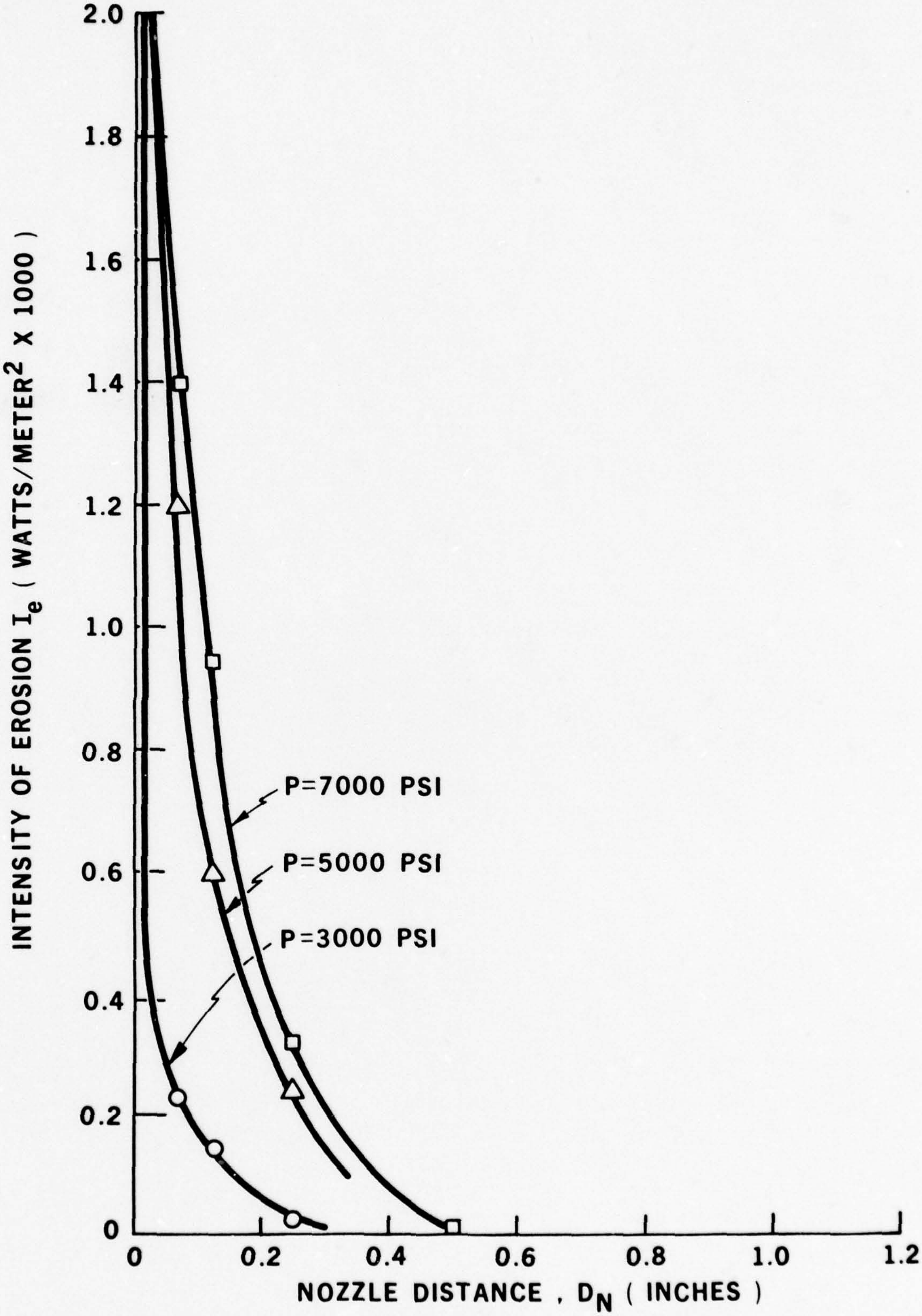

FIGURE 15 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE DISTANCE FOR A 0.047 IN. DIAMETER NOZZLE WITH A NUMBER 45 SWIRL INSERT AT THREE PRESSURES

DAEDALEAN ASSOCIATES, Inc.

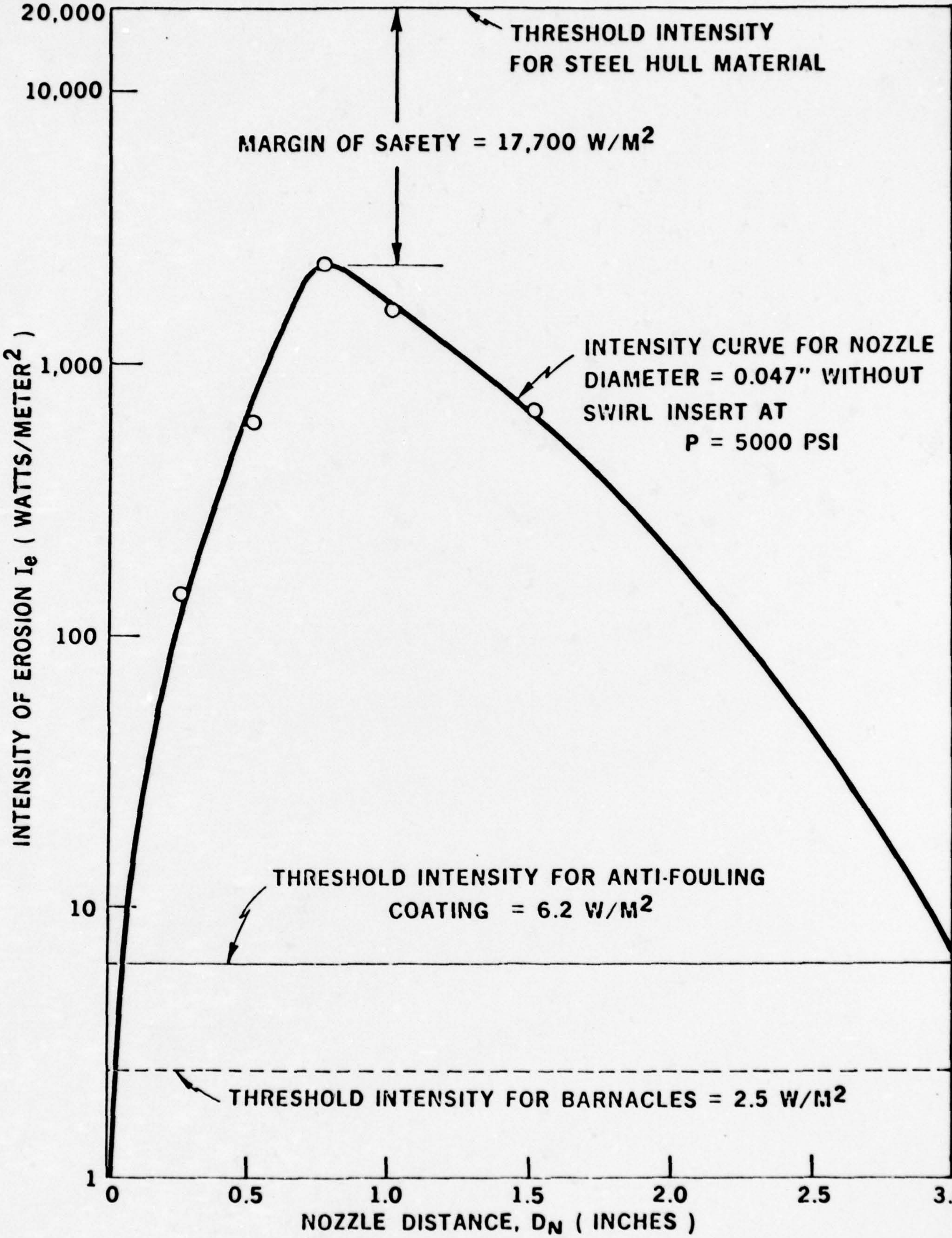

FIGURE 16 INTENSITY OF EROSION FOR 0.047 IN. DIAMETER NOZZLE SHOWING THRESHOLD INTENSITIES FOR ANTI-FOULING COATING AND BARNACLES

DAEDALEAN ASSOCIATES, Inc.

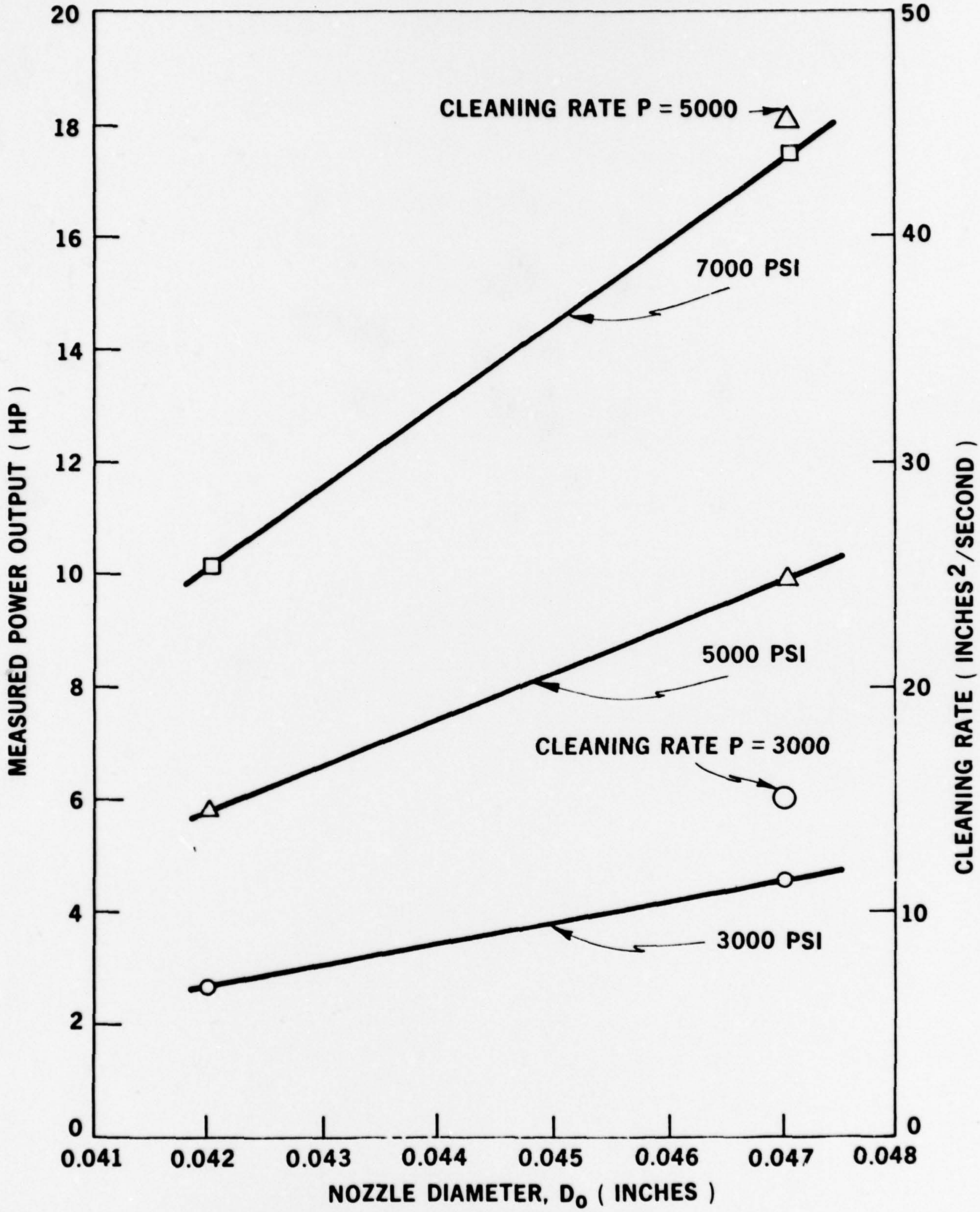

FIGURE 17 MEASURED POWER OUTPUT AND CLEANING RATE AS A FUNCTION OF NOZZLE DIAMETER FOR THREE NOZZLE PRESSURES USING SINGLE ORIFICE NOZZLES WITH NO SWIRL

DAEDALEAN ASSOCIATES, Inc.

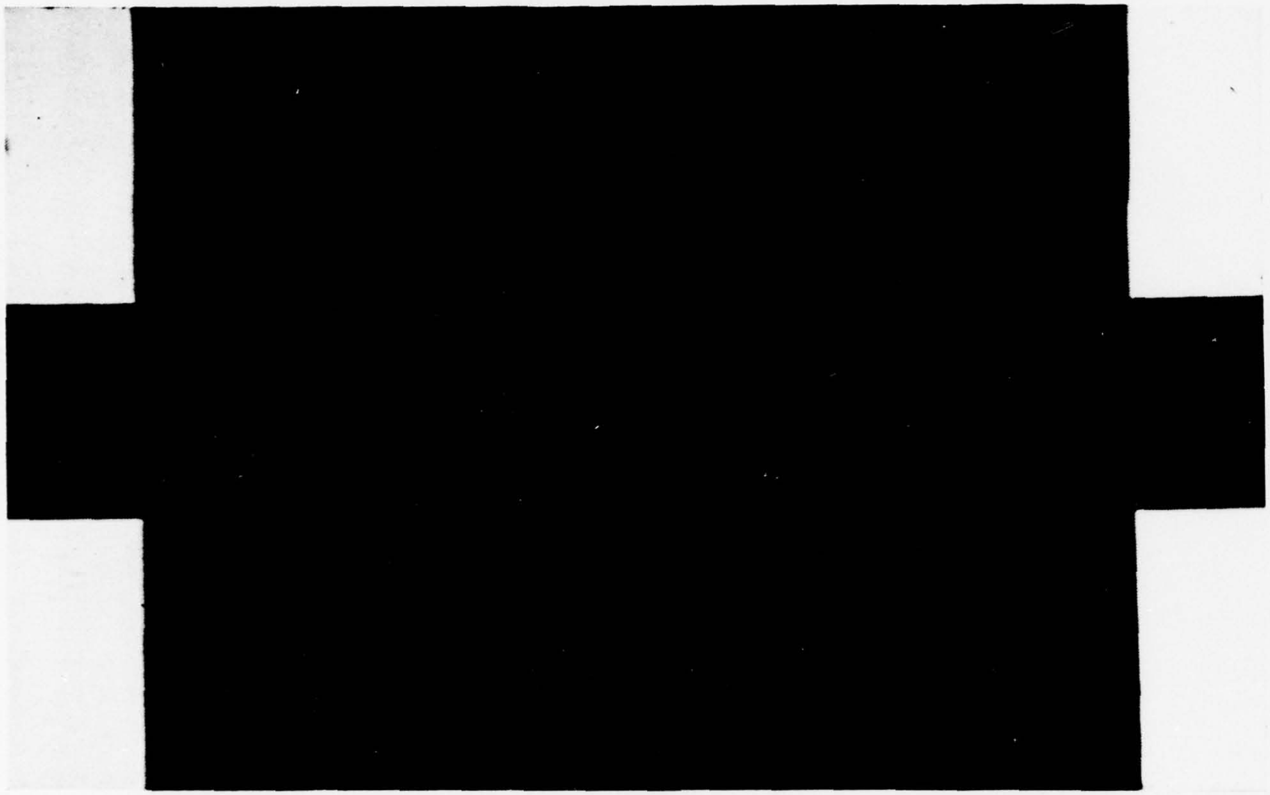

FIGURE 18 TEST SPECIMEN AFTER CLEANING WITH CONCAVER SYSTEM
SHOWING UNDAMAGED ANTI-FOULING COATING

APPENDIX A

DESCRIPTION OF CAVITATION PHENOMENA

In most engineering contexts, cavitation is defined as the process of formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature. In general, a liquid is said to cavitate when vapor bubbles are observed to form and grow as a consequence of pressure reduction. When the phase transition is a result of pressure change by hydrodynamic means, a two-phase flow composed of a liquid and its vapor is called a cavitating flow. While these definitions imply a distinction between phase transitions associated with reduction of pressure, on the one hand, and addition of heat (i.e. boiling), on the other, heat-transfer effects may play an important role in many cases of cavitating liquids. Such effects are especially of importance in liquids near their boiling points. From a purely physical-chemical point of view, of course, no distinction need be made between boiling and cavitation, at least insofar as the question of inception is concerned, and many of the basic physical ideas regarding inception, vapor mass transfer, and condensation apply equally.

As cavitation just begins, tiny vapor bubbles form in rapid succession at the point of lowest pressure and are carried downstream by the flow into a zone of higher pressure, where they immediately collapse as the vapor within them condenses. The process of formation and collapse is so nearly instantaneous

that with the naked eye only a continuous opaque blur can be distinguished. However, as each of the countless individual bubbles collapses, the resulting impact of opposing masses of liquid produces an extremely great local pressure which is transmitted radially outward with the speed of sound, followed by a negative pressure wave which may lead to one or more repetitions of the vaporization-condensation cycle. Boundary materials in the immediate vicinity are therefore subject to rapidly repeated stress reversals and may eventually fail through fatigue, the first sign of which is cavitation erosion.

An increase in the velocity of flow beyond that required for incipient cavitation can produce no further reduction in pressure at the point of cavitation, but merely an elongation of the zone over which the vapor limit prevails. At the same time the size of the vapor bubbles increases, until at advanced stages a more or less stable vapor pocket is formed, which is very similar in shape to the zone of separation next to an unstreamlined boundary. Since the formation of such a pocket must result in a change of the surrounding flow pattern, it is to be expected that the pressure distribution will change accordingly, the pressure necessarily remaining at its vapor limit throughout the length of the cavitation pocket.

For the purposes of this program, the phenomena of cavitation is the formation, growth and collapse of vapor cavities formed from nuclei. Water will provide the continuous medium

for the cavitation process. As the vapor cavities form in the vicinity of the cavity envelope, the fouling is removed from the surface (Figure A-1). Figure A-2 is a photographic representation of the cavity envelope during which the cavitation process is developed. The process is initiated from a nuclei which forms, grows to critical size and collapses. Recent experiments conducted at the DAEDALEAN facilities have determined the feasibility of this process as a method of effectively cleaning marine growth from ship hulls.

CAVITATION INCEPTION PARAMETER

A useful index for the cavitation phenomenon is formulated by introducing for the symbol P in the pressure parameter its minimum value P_v, the result being called the cavitation number:

$$\sigma = \frac{P_o - P_v}{\frac{1}{2}\rho \; V_o^{\,2}} \qquad [1]$$

where: P_o = free stream pressure

P_v = vapor pressure of liquid

V_o = free stream velocity

ρ = density of liquid

So long as σ has an appreciably greater numerical value than the minimum ordinate on the dimensionless pressure-distribution curve for a body of given form, the occurrence of cavitation is not to be expected at any point on the boundary. Once σ becomes approximately equal in absolute magnitude to the minimum ordinate, on the other hand, conditions of incipient cavitation should prevail, and at values of σ below this critical limit σ_i a marked effect upon the pressure distribution is to be expected.

In the case of body forms which result in separation, it is to be noted that cavitation will generally begin within the fine-scale eddies formed at the separation surface long

before the boundary pressure attains its vapor limit. As a result, it is then not possible to predict the magnitude of σ_i either by analytical means or by actual measurement of the pressure distribution in flow without cavitation. On the other hand, not only are boundary forms which properly guide the flow most subject to analytical determination, but they are also those least subject to cavitation. The process of streamlining, in other words, simultaneously lowers the magnitude of σ_i (i.e., the tendency toward cavitation) and makes it more accurately predictable by analytical means.

The cavitation inception parameter is to be experimentally determined in order to evaluate the optimum operating parameters and the efficiency of cleaning by the cavitating jet technique.

CAVITATING JET CLEANING TECHNIQUE

Cavitation cleaning is caused by the collapse of bubbles at or near the solid boundaries guiding high speed flow. Since the early cavitation experiences were encountered on ship propellers in a highly corrosive medium (seawater), there were some controversies as to whether the mechanism was corrosion or mechanical removal. However, it is now generally accepted that the high pressures caused by the collapse of bubbles produce mechanical removal of material. During the process of cavitation a certain volume of material is removed from the surface as a result of the work done by the bubble collapse forces. The energy absorbed by the material is given by:

$$E = \Delta V \cdot S \qquad [2]$$

where: E = energy absorbed by the material removed

ΔV = volume of material removed

S = scale strength which represents the energy absorbing capacity of the material per unit volume under the action of the forces.

The intensity of cavitation is then defined as the power absorbed by the material per unit area and given by:

$$I = \frac{\Delta V \cdot S}{A \cdot \Delta t} \qquad [3]$$

or

$$I = \frac{\Delta y}{\Delta t}\left(S\right) \qquad [4]$$

where: A - area of cleaning

Δy = mean depth of scale = $\frac{\Delta V}{A}$

Δt = exposure time

This is the output intensity of cleaning as seen by the material; similarly one can derive an expression for the bubble collapse intensity which is the input to the cleaning process.

$$\left(\frac{\Delta y}{\Delta t}\right) \cdot \left(S\right) \alpha \ (P_i) \cdot (R) \cdot (n) \qquad [5]$$

where: P_i = impact pressure

R = size of the bubble or jet

n = number of impacts per unit time

These ideas have been incorporated into a master chart for cavitation cleaning as shown in Figure A-3. In this chart, the intensity of erosion is plotted against the rate of mean depth of erosion for various materials ranging from soft lead to very highly resistant stellites. The range of intensities typical of practical machines varies from 10^3-10^4 in.-lb/year-in.^{2}. (The screening tests such as the vibratory test and

rotating disk test operate at intensity levels on the order of 10^5 in.-lb/year-in.^{2} (1 watt/m^2)). The depth of erosion is generally in the range of a fraction of an inch per year. Chemical corrosion rates on steels are in the range of 10^{-3}-10^{-2} in. per year (ipy). Erosion rates on the order of 1 ipy represent serious erosion which may warrant operational limitation or redesign.

The level of threshold intensities for various metals are on the order of 10^{-1} w/m^2 at the most. Elimination of cavitation by the substitution of one metal for another is possible only up to this level of intensity. For this reason, the usefulness of cathodic protection also seems to be limited at this level. If one is prepared to tolerate some erosion and periodic maintenance, then the materials selected coupled with cathodic protection can possibly extend the allowable intensity levels up to 1 w/m^2. However, if the intensity levels are higher than these values, then the foregoing protection methods may not work. In such cases, hydrodynamic redesign, air injection, and specifying limits for operation are the alternate remedial possibilities.

Another tool for the benefit of designers and operators is a multipurpose nomogram as shown in Figure A-4. It provides a visual idea of the range of intensities encountered in actual practice within the range of the depth of cavitation material used and time of operation. It also provides a

quick and easy method of estimating the intensity of cavitation for a given field installation. Lastly, the selection of better materials, if available, is easily made.

From such tools as the master chart and the nomogram, it is possible to estimate the intensity of cavitation required to remove the marine growth and fouling most efficiently at the optimum rate of cleaning without damage to the undercoating and ship hull. The intensity of cleaning can be adjusted to the required level.

The specific advantages of utilizing cavitation jet cleaning for marine growth and fouling removal are as follows:

1. Cavitating water jet cleaning method is relatively simple and reliable.
2. Power requirements would be minimized because of the cavitation phenomenon.
3. Readily available U. S. Navy pump available under most operating mission profiles can be used for cleaning purposes.
4. The possibility of damaging the undercoating that exists when using other mechanical methods of cleaning, including brushes, is eliminated.
5. The ship hulls can be cleaned in wet docking without having to dry-dock them for hull cleanings thus saving considerable amount of docking time and labor.

6. Preliminary results obtained at DAEDALEAN ASSOCIATES, Inc. indicates that cavitating water jet cleaning results in the uniform removal of marine fouling.

The approach in this program was to use fouled plates obtained from U. S. Navy laboratories in order to generate the optimization parameters for efficiently removing the marine growth and fouling from the hull of the ship. Once the optimization of the parameters has been developed and characterized, on-site hull cleaning will be evaluated and cleaning rates established. The understanding and development of the optimum system parameters would lead to the most efficient cleaning operation in terms of cleaning rates, time and cost.

DAEDALEAN ASSOCIATES, Inc.

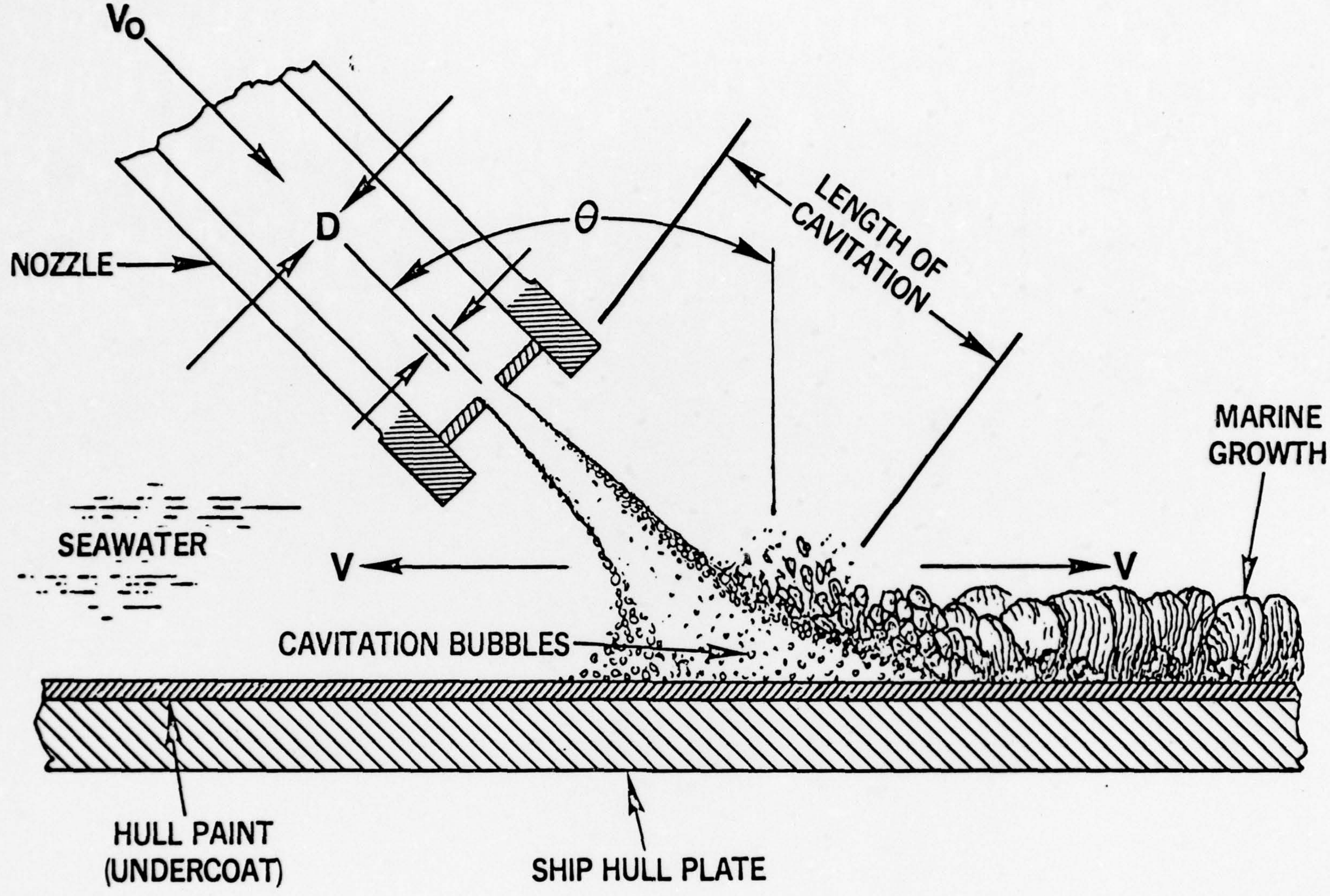

FIGURE A-1 PRINCIPLE OF CAVITATION CLEANING TECHNIQUE AS APPLIED TO REMOVAL OF MARINE GROWTH AND FOULING FROM SHIP HULLS

DAEDALEAN ASSOCIATES, Inc.

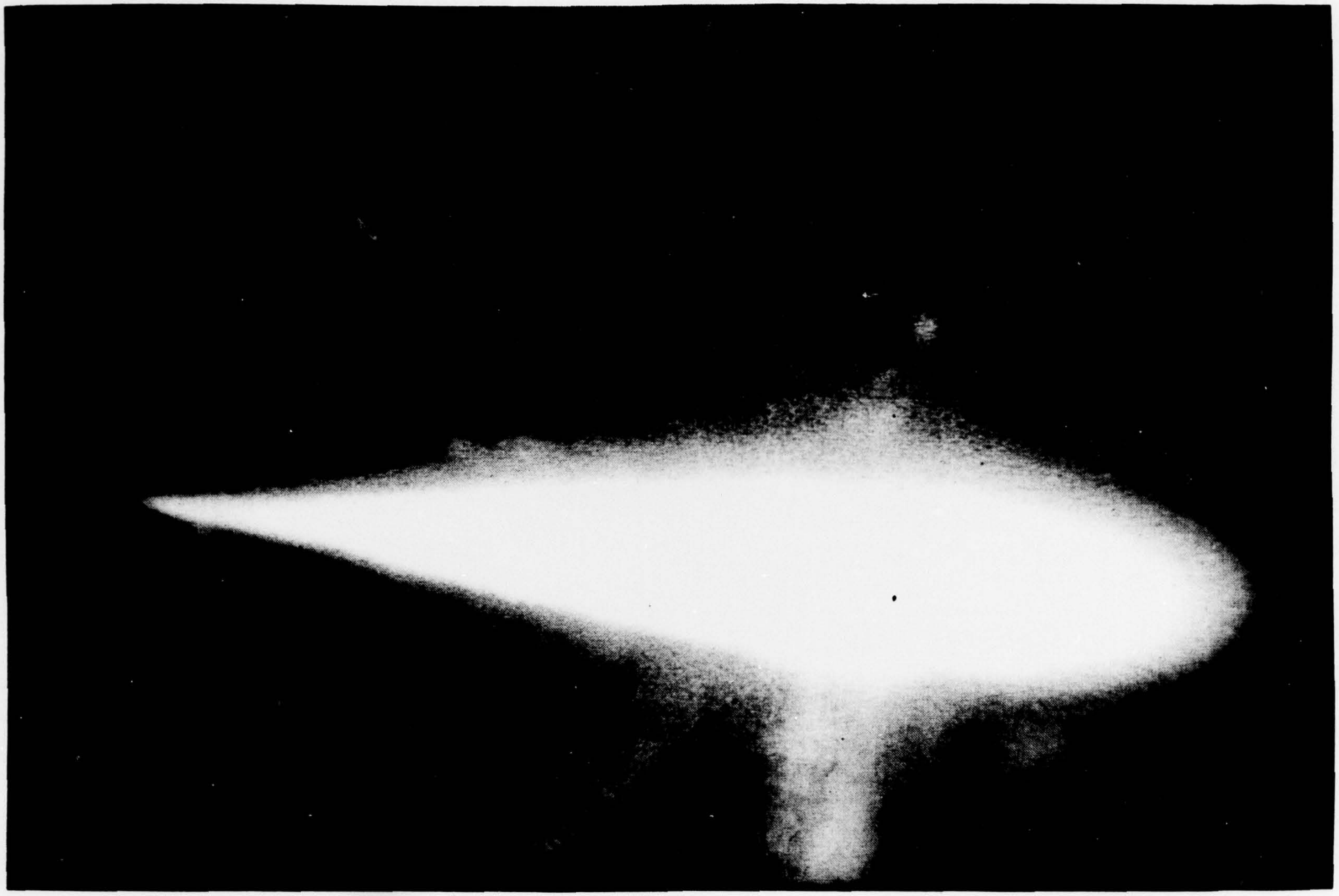

FIGURE A-2 PHOTOGRAPHIC REPRESENTATION OF THE CAVITATING ENVELOPE DURING WHICH TIME THE BUBBLES FORM A NUCLEI, GROW TO CRITICAL SIZE AND COLLAPSE IN THE CONTINUOUS CAVITATION PROCESS

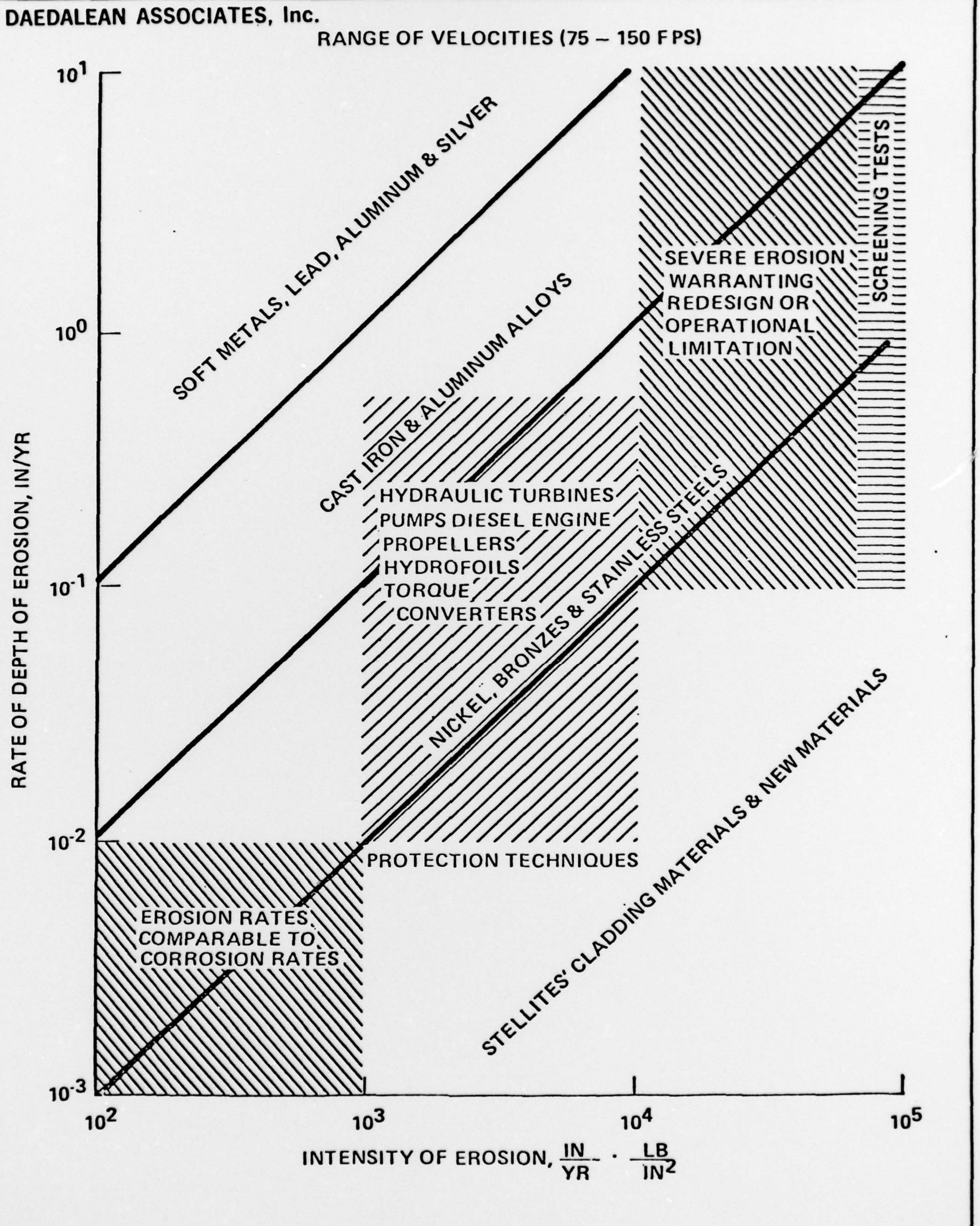

FIGURE A-3 MASTER CHART FOR CAVITATION EROSION

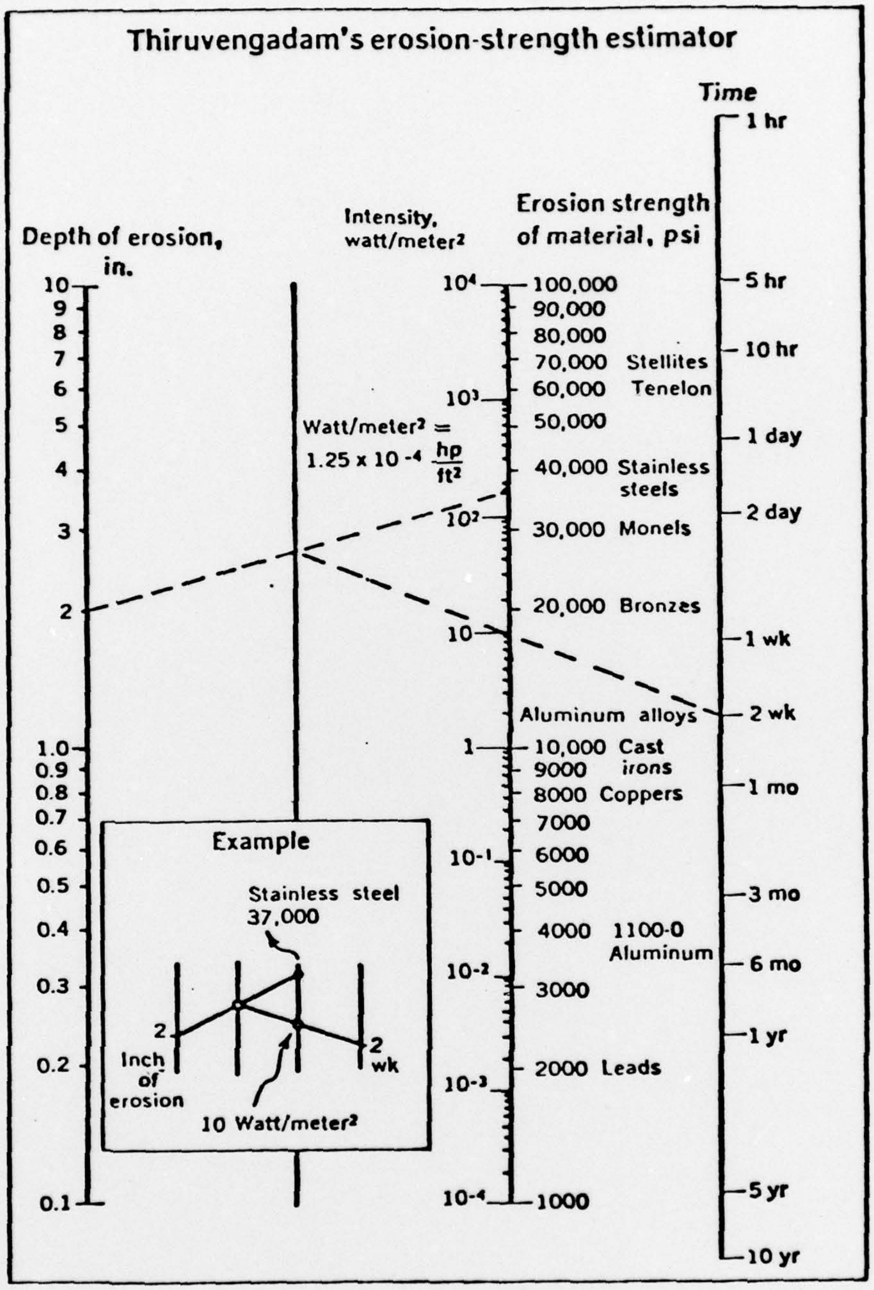

FIGURE A-4 EROSION INTENSITY ESTIMATOR